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U.S. FISH & WILDLIFE SERVICE
REGION 6

ENVIRONMENTAL CONTAMINANTS PROGRAM

Reserve Pit Management: Risks to Migratory Birds

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Executive Summary

This document is intended to help U.S. Fish and Wildlife Service (Service) employees and other natural resource managers understand reserve pits, their uses, associated mortality risk to birds and other wildlife, and alternatives to the use of reserve pits in drilling for oil and gas. The information is provided to help Service employees in the review of oil and gas development projects and development of recommendations to prevent or minimize impacts to Service trust resources such as migratory birds, federally-listed threatened and endangered species, and National Wildlife Refuge system lands. The document also provides a summary of state and federal oil and gas rules that relate to reserve pits.

Earthen pits, also known as reserve pits, excavated adjacent to drilling rigs are commonly used for the disposal of drilling muds and well cuttings in natural gas or oil fields. The contents of reserve pits depend on the type of drilling mud used, the formation drilled, and other chemicals added to the mud circulation system during the drilling process. If the reserve pit contains oil or oil-based products (*i.e.*, oil-based drilling fluids), the pit can entrap and kill migratory birds and other wildlife. During the drilling process, reserve pits probably do not attract aquatic migratory birds such as waterfowl due to human activity and noise. However, once the drilling rig and other equipment are removed from the well pad, the reserve pit is attractive to birds and other wildlife. Birds are attracted to reserve pits by mistaking them for bodies of water. Insects entrapped in reserve pit fluids also attract songbirds, bats, amphibians, and small mammals. The sticky nature of oil entraps birds in the pits and they die from exposure and exhaustion. Birds and other wildlife can also fall into oil-covered reserve pits when they approach the pit to drink.

Following well completion, reserve pits are often left in place after the drilling rig and other equipment are removed from the site. Reserve pit fluids are allowed to dry and the remaining solids are encapsulated with the reserve pit synthetic liner and buried in place. Depending on state regulations, oil operators are allowed from 30 days to one year after well completion to close a reserve pit. The longer the reserve pit is left on site, the greater the probability that aquatic birds will land on the pit. If the reserve pit contains oil, condensates, or other hydrocarbons or hydraulic fracturing fluids, the risk of bird mortality is very high. Hydraulic fracturing fluids can contain chemicals that may be harmful to birds (*e.g.*, surfactants, hydrochloric acid, caustic potash, and diesel fuel).

Bird and other wildlife mortality in reserve pits is preventable. Several states recommend or require netting or screening of reserve pits containing oil to prevent access by wildlife. Immediate removal of the drilling fluids after well completion is the key to preventing wildlife mortality in reserve pits. An alternative to the use of earthen reserve pits is closed-loop drilling systems using steel tanks to hold the drilling muds and cuttings. Other options to dispose of drilling wastes include: downhole injection; solidification and burial; or treatment and reuse.

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Introduction

Earthen pits excavated adjacent to drilling rigs are commonly used for the disposal of drilling muds and well cuttings in oil and gas fields (Figure 1). These pits are referred to as reserve pits. The contents of reserve pits depend on the type of drilling mud used, the formation drilled, and other chemicals added to the mud circulation system during the drilling process.

Figure 1. Reserve pit adjacent to a drilling rig near La Barge, Wyoming.
(USFWS Photo by P. Ramirez)

Reserve pit size depends on well depth. The average reserve pit volume for wells less than 4,000 feet in depth is approximately 3,600 barrels (bbls) and for wells greater than 15,000 feet in depth is more than 15,000 bbls (USOTA 1992). Reserve pits in the Pinedale Anticline and Jonah natural gas fields in Wyoming average 0.6 acres in size (approximately 120 by 200 feet). Reserve pits in the natural gas fields near Wamsutter, Wyoming average 0.3 acres in size (approximately 85 by 140 feet).

Drilling fluids or muds consist of a base fluid or carrier (water, diesel, mineral oil, or a synthetic compound), weighting agents (typically barium sulfate or barite), and bentonite clay to remove the cuttings from the well and line the walls of the hole (Figure 2). Drilling fluid also contains lignosulfonates and lignites to keep the mud in a fluid state. Water-based muds are typically used in drilling due to their lower cost. Oil-based muds are used in wells drilled in reactive shales, deep wells, and horizontal and extended-reach wells, where drilling is more difficult and water-based muds do not perform as well. Synthetic-based muds use nonaqueous fluids (other than oils) as their base and include internal olefins, esters, linear alpha-olefins, poly alpha-olefins, and linear paraffins. Synthetic-based muds have drilling properties similar to those of oil-based muds but do not have polynuclear aromatic hydrocarbons (PAHs), are less toxic, biodegrade faster, and have a lower bioaccumulation potential.

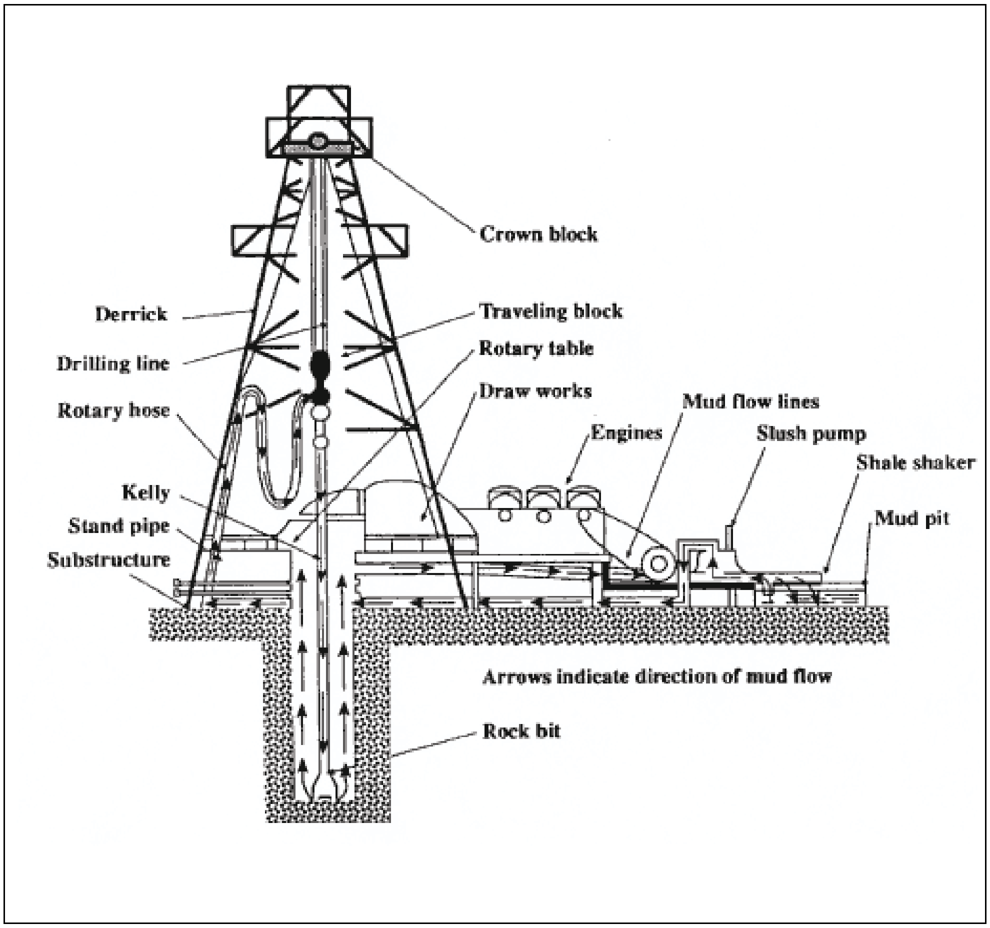

Figure 2. Rotary drilling rig diagram with reserve pit (mud pit).

Following well completion, reserve pits are left in place after the drilling rig and other equipment are removed from the site (Figure 3). Reserve pit fluids are allowed to dry (Figure 4) and the remaining solids are encapsulated with the reserve pit synthetic liner and buried in place (Figure 5).

Figure 3. Reserve pit at a completed well site near Parachute, Colorado. (USFWS Photo by P. Ramirez)

Figure 4. Reserve pit after fluids have evaporated. (USFWS Photo by P. Ramirez)

Figure 5. On-site burial of reserve pit wastes, Carbon County, Wyoming.

Contaminants in Reserve Pits

Reserve pits can contaminate soil, groundwater, and surface water with metals and hydrocarbons if not managed and closed properly. As reserve pit fluids evaporate, water-soluble metals, salts, and other chemicals become concentrated. Precipitation, changes in shallow groundwater levels, and flooding can mobilize these contaminants into adjacent soils and groundwater. Liners most often do not adequately seal the drilling wastes, especially if they are torn (Figure 6). Beal *et. al*. (1987) documented the migration of leachate 400 feet from reserve pits buried in 1959 in north-central North Dakota and reported groundwater contamination 50 feet below the buried reserve pits. Migration of salts from buried drilling wastes from unlined reserve pits has been documented in U.S. Fish and Wildlife Service (Service) managed Waterfowl Production Areas in northeastern Montana and northwestern North Dakota (K. Nelson, U.S. Fish & Wildlife Service, pers. com., Dec. 10, 2008). Caustic soda, rig wash, diesel fuel, waste oil from machinery, and other refuse could be placed in reserve pits either deliberately or inadvertently. Reis (1996) states that "improper reserve pit management practices have created sources of benzene, lead, arsenic, and fluoride, even when these contaminants were not detected or were not present in the drilling mud system." Water-based drilling muds can contain glycols, chromium, zinc, polypropylene glycol, and acrylamide copolymers (Fink 2003). Synthetic-based muds contain mineral oil and oil-based muds can contain diesel oil, although diesel oil is being replaced by a palm oil derivative or hydrated caster oil (Fink 2003).

Other additives typically used in drilling fluids include: polymers (partially hydrolyzed polyacrylamide (PHPA) and polyanionic cellulose (PAC)); drilling detergents; and sodium carbonate (soda ash) (Papp 2001). PHPA is used to increase viscosity of fluid and inhibit clay and shale from swelling and sticking. PAC is used to increase the stability of the borehole in unconsolidated formations. Drilling detergents or surfactants are used with bentonite drilling fluids to decrease the surface tension of the drill cuttings. Soda ash is used to raise the pH of the water and precipitate calcium out of the water.

Figure 6. Reserve pit with torn synthetic liner. (USFWS Photo by P. Ramirez)

Disposal of Drilling Wastes

The most recent data on drilling waste disposal by the American Petroleum Institute (API) (2000) shows the oil industry used reserve pits in 68 percent of the oil and conventional natural gas wells drilled in 1995 and closed loop drilling systems in 25 percent of the wells. An estimated 92 percent of onshore drilling wastes were derived from freshwater based mud systems, compared to 64 percent of drilling wastes in 1985. In 1995, 68 percent of drilling wastes were disposed onsite through evaporation and burial. Approximately 1.2 bbls of drilling waste are produced per foot of well depth drilled (API 2000). In 1995, an estimated 148 million bbls of drilling waste were produced. According to the U.S. Energy Information Administration, a total of 335 million feet were drilled in the exploration and development of oil and natural gas in 2008 (EIA 2009). Assuming the drilling of those wells resulted in an average of 1.2 bbls of drilling waste per foot of well depth drilled; approximately 402 million bbls of drilling waste were produced in 2008.

On-site Disposal and Burial of Reserve Pit Wastes

On-site disposal and burial involves allowing reserve pit fluids to dry and encapsulating the remaining solids with the reserve pit synthetic liner and burying the wastes in place. Depending on state regulations, oil operators are allowed from 30 days to one year after well completion to close a reserve pit. Assuming that 68 percent of the drilling wastes are currently disposed onsite through evaporation and burial, an estimated 273 million bbls of drilling wastes were disposed onsite in 2008.

Solidification of Drilling Wastes

If reserve pits must be used, cost-effective technology exists to solidify pit fluids immediately following well completion. Solidification can add to the waste volume but prevents mobilization of potential contaminants into the soil and/or groundwater (EPA 2000). Solidification involves the removal of the free liquid fraction of reserve pit fluids and then adding solidifiers such as commercial cement, fly ash, or lime kiln dust. Removal and off-site disposal of liquids removes most of the water soluble metals, salts, and chemicals from the drilling waste material.

Pitless or Closed Loop Drilling

Pitless drilling or closed-loop drilling reduces the amount of drilling waste, recycles drilling fluids, and reduces drilling costs (Rogers et. al. 2006a and b). Pitless drilling can reduce the volume of waste by 60 to 70 percent (Rogers et. al. 2006b). Pitless drilling also conserves water and prevents soil contamination.

Pitless drilling systems are equipped with a “chemically-enhanced” centrifuge that separates drilling mud liquids from solids (Rogers et. al. 2006b). The separated drilling mud solids are stored in a steel tank and then transferred to a synthetically-lined clay pad for drying (Figure 7). The pads are designed to prevent the runoff of any liquids. The drill cuttings are either buried on site or are transferred to an approved commercial disposal facility for disposal (Rogers et. al. 2006b). The drill cuttings can create environmental problems and pose a risk to wildlife if the trench or excavated burial pit collects water from snowmelt or rainfall. Ponded water in the trench or burial pit may become contaminated with hydrocarbons present in the drill cuttings. Immediate burial of drill cuttings and contouring of the site should prevent the ponding of snowmelt or rainwater. Sheens, oil, and sludges in the disposal pit will pose a risk to migratory birds and other wildlife (Figures 8 and 9). Additionally, if the pits are not lined, soil and groundwater contamination can occur if the drill cuttings contain leachable concentrations of hydrocarbons and metals.

Treatment and Reuse of Drilling Fluids

Operators in the Jonah natural gas field in southwestern Wyoming are currently using new technology to treat and reuse drilling fluids (Figure 10). Drilling fluids are treated using a patented combination of fluid and thermal dynamics to remove oil and salts. The treatment separates the drilling fluid into fresh water, heavy brine, condensate, and methanol. The condensate is recovered and sold. The methanol and brine are reused in drilling fluids. The fresh water is either reused at other drilling locations or is used for the benefit of livestock or wildlife.

Figure 7. Closed-loop or pitless drilling site with synthetically-lined pad for temporary storage of drill cuttings.

Figure 8. Trench used for burial of drill cuttings from closed-loop drilling. Sheens are visible on the water surface. (USFWS Photo by P. Ramirez)

Figure 9. Ponding of snowmelt and rainfall in trench used for the disposal of drill cuttings from closed-loop (pitless) drilling system.

Figure 10. Treatment facility at the Jonah Gas Field, Sublette County, Wyoming used to separate condensate, methanol, brine, and water from drilling fluids.
(USFWS Photo by P. Ramirez)

Down-hole Disposal of Drilling Fluids

Oil operators in Alaska inject the drill cuttings underground after the solids are finely ground and mixed with a liquid to form a slurry (Veil and Dusseault 2003). This disposal technique is typically used in conjunction with pitless drilling. Open earthen reserve pits are not used to temporarily store the drilling fluids. The elimination of open pits removes the mortality threat to migratory birds and other wildlife. Slurry injection of drilling wastes also poses less environmental impacts when properly managed and monitored as the wastes are disposed deep underground and isolated from aquifers (Veil and Dusseault 2003).

Threats to Migratory Birds

Reserve pits containing oil or oil-based products (i.e. oil-based drilling fluids) can entrap and kill migratory birds and other wildlife. Birds, including hawks, owls, waterfowl, and songbirds, are attracted to reserve pits by mistaking them for bodies of water. Reserve pits also attract other wildlife such as insects, bats, small mammals, amphibians, and big game. Wildlife can fall into oil-covered reserve pits while attempting to drink along the pits' steep sideslopes. The steep, synthetically-lined pit walls make it almost impossible for entrapped wildlife to escape. Insects entrapped in the oil can also attract songbirds, bats, amphibians, and small mammals. The struggling birds or small mammals in turn attract hawks and owls to the oil-covered pit. The sticky nature of oil entraps birds in the reserve pits and they die from exposure and exhaustion. Birds that do manage to escape die from starvation, exposure or the toxic effects of oil ingested during preening. Birds ingesting sublethal doses of oil can experience impaired reproduction. Cold stress can kill the animal if oil damages the insulation provided by feathers or fur. Animals not killed in the reserve pits can suffer ill effects later from contact with the oil and chemicals in the pits. If they absorb or ingest oil in less than acutely lethal amounts they may suffer a variety of systemic effects and may become more susceptible to disease and predation. During the breeding season, birds can transfer oil from their feet and feathers to their eggs. In some cases, a few drops of oil on an egg shell can kill the embryo (King and LeFever 1979).

Service law enforcement agents and environmental contaminants specialists have documented bird mortality in reserve pits in Colorado, Montana, North Dakota, Utah, and Wyoming. The presence of small amounts of hydrocarbons, such as diesel, and condensate, can create sheens on the reserve pit fluid. The presence of visible sheens on reserve pit fluids is just as deadly to birds that come into contact with them (Figure 11). A light sheen will coat the bird's feathers with a thin film of oil. Although light oiling on a bird may not immediately immobilize the bird, it will compromise the feathers' ability to insulate the bird. Furthermore, the affected bird will ingest the oil when it preens its feathers and suffer acute or chronic effects.

Well stimulation chemicals, such as corrosion inhibitors and surfactants, disposed into reserve pits, pose additional risk to migratory birds. Surfactants reduce the surface tension of water; thus, allowing water to penetrate through feathers and onto skin. This compromises the insulation properties of the feathers and subjects the bird to hypothermia (Stephenson 1997). Furthermore, loss of water repellency in feathers due to reductions in surface tension will cause the bird to become water logged.

Figure 11. Reserve pit with visible sheen on surface. Sheens on the fluid surface can be lethal to birds landing on reserve pits. (USFWS Photo by P. Ramirez)

Loss of buoyancy will cause the bird to drown. Stephenson (1997) reports that water surface tension reduced to approximately 38 to 50 mNm^{-1} will cause feather wetting in adult waterfowl and could result in potential mortality. The unit mNm^{-1} is defined as microNewtons per meter, the force necessary to break a film of a given length. Pure water has a surface tension of approximately 72 mNm^{-1}. Storage of hydraulic fracturing (frac) fluids in reserve pits can present a risk to migratory birds if the frac fluids contain hydrocarbons or surfactants.

During the drilling process, human activity and noise discourage aquatic migratory birds such as waterfowl from accessing reserve pits. However, once the drilling rig and other equipment are removed from the well pad, the reserve pit is attractive to birds and other wildlife. The longer the reserve pit is left on site, the greater the probability that aquatic birds will land on the pit. If the reserve pit contains oil, condensates, or other hydrocarbons or surfactants, the risk of bird mortality is very high. Mortality events are episodic in reserve pits. Total bird carcasses recovered from individual reserve pits range from a few birds to large mortality incidents involving many birds. The largest mortality incident in Wyoming occurred at a reserve pit in Carbon County where Service personnel recovered 77 birds, primarily puddle ducks, between July 2008 and September 2008 (Figure 12 and 13). The pit remained at the well site for over a year and contained oil and sludges on the surface.

Bird carcasses recovered from reserve pits in Colorado, Montana, North Dakota, and Wyoming include passerine songbirds, raptors, shorebirds and waterfowl (Table 1 and Figure 14). Service personnel have observed songbirds landing at the edges of reserve pits and drinking water from pits.

Figure 12. Reserve pit in Carbon County, Wyoming, site of a large waterfowl mortality incident (77 bird carcasses recovered). (USFWS Photo by P. Ramirez)

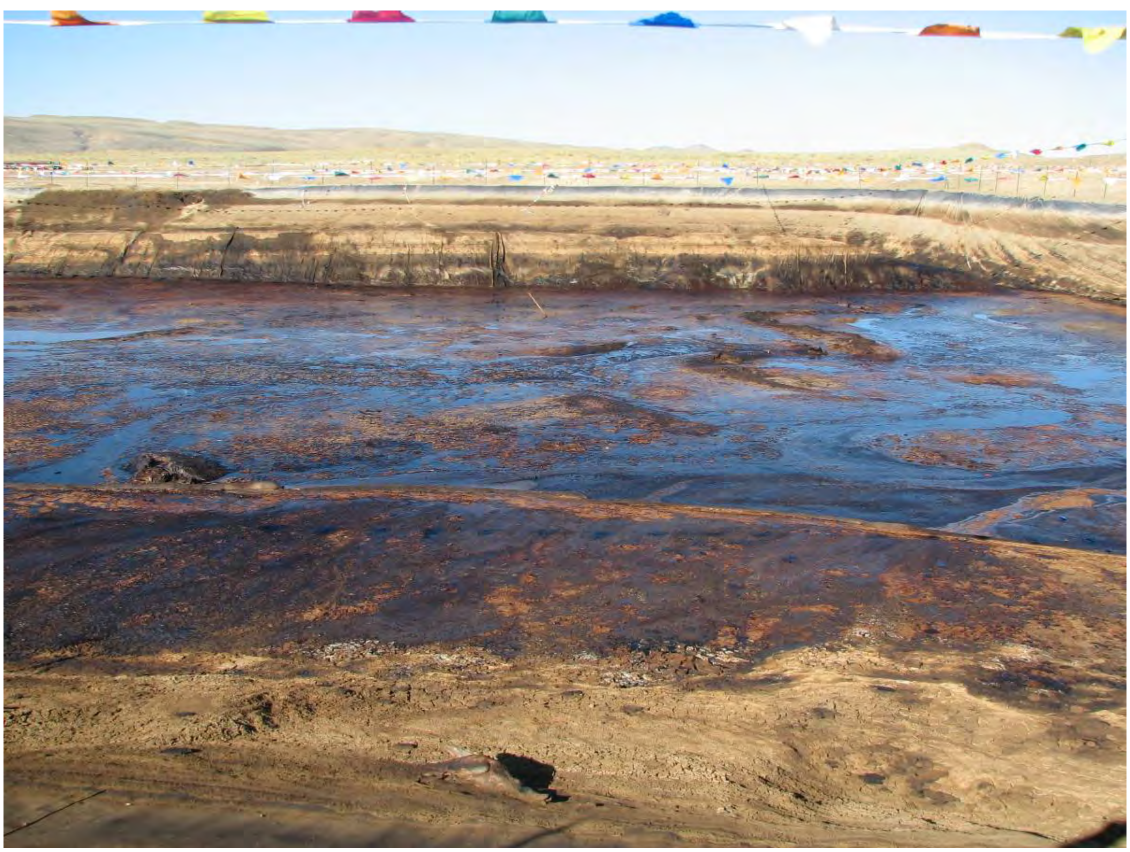

Figure 13. Duck carcass (lower center) in a reserve pit. (USFWS Photo by P. Ramirez)

Table 1. Bird species recovered from reserve pits in Colorado, Montana, North Dakota, and Wyoming.

Waterfowl		**Passerine Birds**	
Mallard	*Anas platyrhynchos*	Eastern Kingbird	*Tyrannus tyrannus*
Blue-winged Teal	*Anas discors*	Horned Lark	*Eremophila alpestris*
Green-winged Teal	*Anas crecca*	Barn Swallow	*Hirundo rustica*
Northern Shoveler	*Anas clypeata*	Gray Catbird	*Dumetella carolinensis*
Common Goldeneye	*Bucephala clangula*	Vesper Sparrow	*Pooecetes gramineus*
Gadwall	*Anas strepera*	Lark Sparrow	*Chondestes grammacus*
		Song Sparrow	*Melospiza melodia*
Other Aquatic Birds		Dark-eyed Junco	*Junco hyemalis*
Grebe		Red-winged Blackbird	*Agelaius phoeniceus*
White-faced Ibis	*Eudocimus albus*	Brewer's Blackbird	*Euphagus cyanocephalus*
		Brown-headed Cowbird	*Molothrus ater*
Raptors		Common Grackle	*Quiscalus quiscula*
Great Horned Owl	*Bubo virginianus*		
American Kestrel	*Falco sparverius*		

Figure 14. Songbird in a reserve pit in North Dakota. (USFWS Photo by P. Ramirez)

Prevention of Bird Mortality in Reserve Pits

Bird and other wildlife mortality in reserve pits is preventable. Several states regulations address or recommend the netting or screening of reserve pits containing oil to prevent access by birds and other wildlife (Figure 15). However, enforcement is inconsistent. Immediate removal of the drilling fluids after well completion is the key to preventing wildlife mortality in reserve pits. The best options are to eliminate the use of open reserve pits and use closed-loop drilling systems or downhole disposal of drill cuttings. Care is still required with closed-loop systems to prevent ponding of water in the solids disposal trenches.

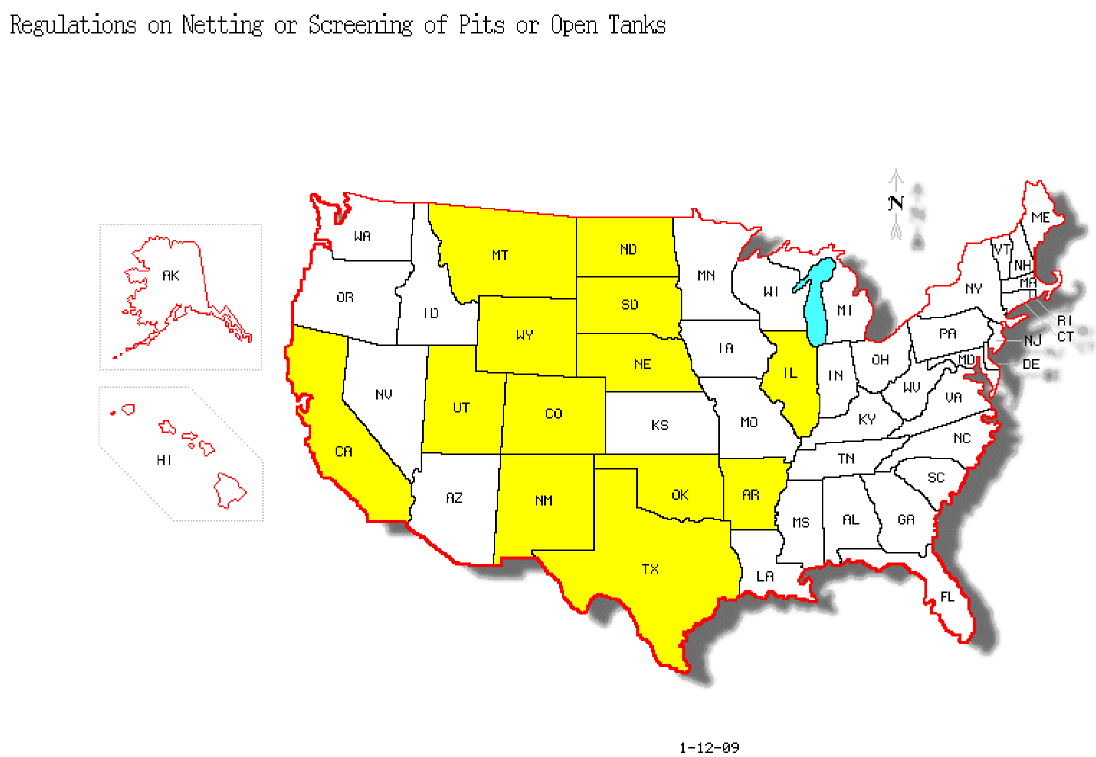

Figure 15. States with oil and gas regulations recommending or requiring netting or screening of pits or open tanks to prevent the mortality of migratory birds and other wildlife.

State and Federal Reserve Pit Regulations

The use of reserve pits for the storage of drilling fluids is regulated by state oil and gas regulatory agencies in private and state-owned mineral estates and by the U.S. Bureau of Land Management (BLM) in federal and tribally-owned mineral estates. Reserve pit construction requirements vary from state to state but generally, the regulations are designed to protect surface and groundwater from contamination.

The BLM requires operators to construct reserve pits at least 50 percent below ground level to prevent pit dike failure. The BLM also restricts the construction of reserve pits in areas with shallow groundwater and requires 2 feet of freeboard on reserve pits.

The BLM provides the following standard operating procedures and guidelines for reserve pits in their *Gold Book* (US DOI 2006).

> *Reserve pits should be appropriately fenced to prevent access by persons, wildlife, or livestock. During drilling in active livestock areas, the reserve pit must be fenced with an exclosure fence on three sides and then fenced on the fourth side once drilling has been completed. Refer to Figure 1 for recommended fence construction standards in active livestock areas. In areas where livestock will not be present, other types of fences may be appropriate. The fence should remain in place until pit reclamation begins. After cessation of drilling and completion operations, any visible or measurable layer of oil must be removed from the surface of the reserve pit and the pit kept free of oil. In some situations and locations, precautions, such as netting, may be required in order to prevent access and mortality of birds and other animals.*

The BLM's **Onshore Oil and Gas Order No. 7 Disposal of Produced Water** also requires fencing and other enclosures to prevent access by livestock, wildlife, and unauthorized personnel**:**

> ***E. Design requirements for pits**. c. The pit shall be fenced or enclosed to prevent access by livestock, wildlife, and unauthorized personnel. If necessary, the pit shall be equipped to deter entry by birds. Fences shall not be constructed on the levees.*

After the well is completed, reserve pits are left in place after the drilling rig and other equipment are removed from the site. Operators typically have up to one year to allow the reserve pit fluids to dry and close the pit. Alabama, Kentucky, and Tennessee allow only 30 days for reserve pit closure while several states allow up to one year (Table 2 and Figure 16).

Table 2. States with specific time frames for reserve pit closure.

State	Pit Closure (in days)*		State	Pit Closure (in days)
Alabama	30		Pennsylvania	270
Kentucky	30		Kansas	365
Tennessee	30		Montana	365
New York	45		Nebraska	365
Mississippi	90		North Dakota	365
Ohio	150		Oregon	365
Arkansas	180		South Dakota	365
Illinois	180		Utah	365
Louisiana	180		Wyoming	365
Michigan	180		Texas	30 to 365
New Mexico	180		Colorado	90 to 180
West Virginia	180		Oklahoma	90 to 365

* Indiana and Virginia require immediate closure of reserve pits after well completion.

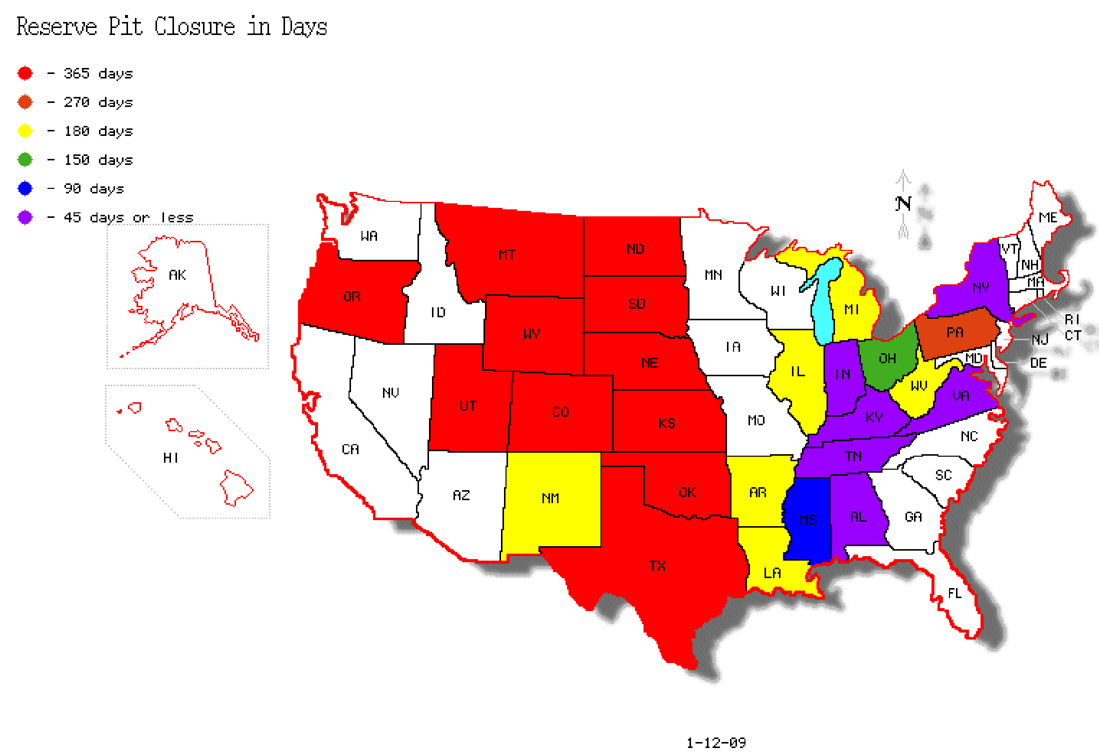

Figure 16. Maximum number of days allowed for the closure of reserve pits following well completion.

Oil operators in Alaska do not use open earthen pits for the disposal and or temporary storage of drilling fluids. The drill cuttings are injected underground. California does not specify a time limit for reserve pit closure; however, the performance bond is not released until the site is reclaimed (including reserve pit closure) (Rob Hauser, California Division of Oil, Gas and Geothermal Resources, pers. com., January 12, 2009). The performance bond release serves as an incentive to close the reserve pit and restore the site as soon as possible. The Maryland Department of the Environment does not specify a time limit for the closure of reserve pits; however, their policy recommends pit closure within 30 days of well completion (Mollie Edsall, Senior Geologist, Maryland Department of the Environment, pers. com., January 14, 2009).

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Appendix A
State Rules and Regulations Pertaining To Reserve Pits

Alaska
20 AAC 25.047. Reserve pits and tankage
(a) Before a person commences drilling a well, a reserve pit must be constructed or tankage installed for the reception and confinement of drilling fluids and cuttings, to facilitate the safety of the drilling operation, and to prevent contamination of freshwater and damage to the surface environment. The confining surface of a reserve pit must be impervious. If practical, confinement diking in construction of a reserve pit must be avoided. If confinement dikes are necessary, they must be kept to a minimum. Dikes must be constructed and maintained to ensure their confinement integrity.

(b) Upon completion, suspension, or abandonment of the well, the operator shall proceed with diligence to leave the reserve pit in a condition that does not constitute a hazard to freshwater.

20 AAC 25.528. Open pit storage of oil
An operator may not, except during an emergency, store or retain crude oil in an open earthen confinement or in an open receptacle.

http://www.aogcc.alaska.gov/Regulations/RegIndex.shtml

Arkansas
RULE B-26 (j) (4) (E) - If the Director determines, based on a review of the information submitted by the operator and surface owner, the pit is not exempted, the pit shall be closed, within six (6) months.

RULE B-26 (c) (8) -All open top tanks shall be covered with bird netting, or other system designed to keep birds and flying mammals from landing in the tank.

http://www.aogc.state.ar.us/OnlineData/Forms/Rules%20and%20Regulations.pdf

Arizona
R12-7-108. **Pit for Drilling Mud and Drill Cuttings** - D. Any mud contained in an earthen pit shall be water-based and contain no more than one pound per barrel of thinner for each 25 pounds per barrel of barite or hematite. Mud containing chromium lignosulfonate, ferrochrome lignosulfonate or other chromium compounds shall not be used.

E. Drilling mud shall be disposed of by either recycling or commercial off-site disposal. Mud described in subsection (D) may be disposed of by evaporation and subsequent leveling of the pits.

http://www.azsos.gov/public_services/Title_12/12-07.pdf

California

1770. Oilfield Sumps. – (b) (3) - (3) Any sump, except an operations sump, which contains oil or a mixture of oil and water shall be covered with screening to restrain entry of wildlife in accordance with Section 1778(d).

1775. Oilfield Wastes and Refuse. – (b) Drilling mud shall not be permanently disposed of into open pits. Cement slurry or dry cement shall not be disposed of on the surface.

3781. The Legislature hereby finds and declares that it is essential in order to protect the wildlife resources of California that all hazardous exposed oil sumps in this state be either screened or eliminated.

3783. Whenever the supervisor receives notification from the Department of Fish and Game pursuant to subdivision (a) of Section 1016 of the Fish and Game Code that an oil sump is hazardous to wildlife, he shall forthwith given written notice of such hazardous condition to the owner, lessee, operator, or person responsible for the existence of the condition and set forth the hazardous conditions as specified by the Department of Fish and Game. The owner, lessee, operator, or person responsible shall, within 30 days from the date of such notification, or such longer period as may be mutually agreed upon by the supervisor, the Department of Fish and Game, and the owner, lessee, operator, or person responsible, clean up or abate the condition to the satisfaction of the supervisor and the Department of Fish and Game. If the owner, lessee, operator, or person responsible does not clean up or abate the condition to the satisfaction of the supervisor and the Department of Fish and Game within the required period of time, the supervisor shall forthwith order the closure of the oil and gas production operation maintaining the oil sump.

3782. The supervisor shall promulgate rules and regulations for the adequate screening of oil sumps to protect wildlife and shall order the closure of any oil and gas production operation maintaining an exposed or inadequately screened oil sump in violation of such rules and regulations.

http://www.conservation.ca.gov/dog/pubs_stats/Pages/law_regulations.aspx

Colorado

902. PITS - GENERAL AND SPECIAL RULES

c. Any accumulation of oil or condensate in a pit shall be removed within twenty-four (24) hours of discovery. Only de minimis amounts of hydrocarbons may be present unless the pit is specifically permitted for oil or condensate recovery or disposal use. A Form 15 pit permit may be revoked by the Director and the Director may require that the pit be closed if an operator repeatedly allows more than de minimis amounts of oil or condensate to accumulate in a pit. This requirement is not applicable to properly permitted and properly fenced, lined, and netted skim pits that are designed, constructed, and operated to prevent impacts to wildlife, including migratory birds.

d. Where necessary to protect public health, safety and welfare or to prevent significant adverse environmental impacts resulting from access to a pit by wildlife, migratory birds, domestic animals, or members of the general public, operators shall install appropriate netting or fencing.

1003. INTERIM RECLAMATION
d. Drilling pit closure. As part of interim reclamation, drilling pits shall be closed in the following manner:
(1) Drilling pit closure on crop land and within 100-year floodplain. On crop land or within the 100-year floodplain, water-based bentonitic drilling fluids, except de minimis amounts, shall be removed from the drilling pit and disposed of in accordance with the 900 Series rules. Operators shall ensure that soils meet the concentration levels of Table 910-1, above. Drilling pit reclamation, including the disposal of drilling fluids and cuttings, shall be performed in a manner so as to not result in the formation of an impermeable barrier. Any cuttings removed from the pit for drying shall be returned to the pit prior to backfilling, and no more than de minimis amounts may be incorporated into the surface materials. After the drilling pit is sufficiently dry, the pit shall be backfilled. The backfilling of the drilling pit shall be done to return the soils to their original relative positions. Closing and reclamation of drilling pits shall occur no later than three (3) months after drilling and completion activities conclude.

(2) Drilling pit closure on non-crop land. All drilling fluids shall be disposed of in accordance with the 900 Series rules. Operators shall ensure that soils meet the concentration levels of Table 910-1, above. After the drilling pit is sufficiently dry, the pit shall be backfilled. Materials removed from the pit for drying shall be returned to the pit prior to the backfilling. No more than de minimis amounts may be incorporated into the surface materials. The backfilling of the drilling pit will be done to return the soils to their original relative positions so that the muds and associated solids will be confined to the pit and not squeezed out and incorporated in the surface materials. Closure and reclamation of drilling pits shall occur no later than six (6) months after drilling and completion activities conclude, weather permitting.

http://cogcc.state.co.us/

Florida
62C 27.001 General. (4) Mud Tanks, Reserve Pits, and Dikes. Before spudding the well, mud tanks of sufficient size to hold the active mud volume at the surface shall be installed for containment of all active drilling fluids. Earthen mud pits shall not be used for this purpose.

http://www.dep.state.fl.us/geology/rules/oilandgasrules.htm

Illinois
Section 240.540 Drilling and Completion Pit Restoration
a) Sediment, drilling fluid circulation and reserve pits, except sediment pits used as completion pits, shall be filled and leveled within 6 months after drilling ceases. Drilling fluid wastes may be disposed of by on-site burial or surface application in accordance with subsection (b) of this Section at the site of drilling. Saltwater or Oil Drilling Fluid wastes shall be removed from the site and disposed of in an Illinois Environmental Protection Agency permitted special waste landfill, injected in a Class II well, disposed of in a well during the plugging process or buried in one of the lined pits and the liner folded over and additional liner material added to completely cover the drilling waste buried at least 5 feet below the ground surface.

Section 240.810 Tanks, Tank Batteries and Containment Dikes

(b) (4) All open top tanks shall be covered with bird netting, or other system designed to keep birds and flying mammals from landing in the tank.

Section 240.861 Existing Pit Exemption For Continued Production Use
(g) (4) All pits shall be covered with bird netting or other systems designed to keep birds and flying mammals from landing in the pit.

http://dnr.state.il.us/legal/adopted/62-240.pdf

Indiana
312 IAC 16-5-12 Mud pits, Authority: IC 14-37-3, Affected: IC 14-37
Sec. 12. (a) An owner or operator shall construct and maintain necessary mud circulation and reserve pits.
(b) Upon completion of a well, pits shall be filled and leveled. The surface shall be restored as nearly as practicable to conditions existing before drilling commenced.
(Natural Resources Commission; 312 IAC 16-5-12; filed Feb 23, 1998, 11:30 a.m.:
21 IR 2342; readopted filed Nov 17, 2004, 11:00 a.m.: 28 IR 1315)

http://www.in.gov/legislative/ic/code/title14/ar37/index.html

Kansas
82-3-602. TIME LIMITATION; PENALTY; CLOSURE OF PITS; CLOSURE FORMS; DRILLING FLUID MANAGEMENT; WASTE TRANSFER; SURFACE RESTORATION.
(a) (1) The time limitation for the closure of each pit, unless otherwise specified in writing by the commission, shall be according to the following schedule:
(A) Drilling pits or haul-off pits shall be closed within a maximum of 365 calendar days after the spud date of a well.
(B) Work-over pits shall be closed within a maximum of 365 days after work-over operations have ceased.

http://www.kcc.state.ks.us/conservation/index.htm

Kentucky
401 KAR 5:090 Section 10 - Drilling Pits
Drilling pits shall be constructed to have the capability and the capacity to contain drilling fluids so that contamination of the waters of the Commonwealth do not occur. Spills or releases having the potential of degrading the environment or impacting human health and safety must be reported to the Environmental Response Team at (502) 564-2380 or 1-800-928-2380. For drilling and workover activities, the following need to be addressed:
- A pit must be constructed which will contain all the cuttings and fluids anticipated for the area and depth to be drilled. Adequate freeboard (distance of fluid level in pit to upper rim) should be maintained and checked regularly during drilling. If necessary, a secondary pit should be constructed in such a manner as to contain or prevent overflow.

• Containment structures should be placed to contain all spilled fuel, crude oil and drilling fluids.
• Consideration given to the type of material used in the construction of the pit to prevent groundwater contamination and leakage.

Within thirty (30) days following completion of drilling activities, the pits shall be closed. Waste shall be removed from the pit and disposed of in accordance with Kentucky laws and regulations. All visible contamination must be removed from the pit during closure. The appropriate waste disposal method is dependent upon the waste's components (make-up). The pit area shall be backfilled, graded and revegetated. The vegetative cover shall be capable of preventing soil erosion. Pits in place longer than thirty (30) days shall be considered as "Holding Pits" and shall meet their requirements (See Holding Pits). However, the Director of the Division of Water may, with good cause, extend the pit's life up to a maximum of ninety (90) days. A written request seeking that extension should be submitted before the day of completion

401 KAR Chapter 30, 401 KAR 31:030, 401 KAR 47:030 and 401 KAR 47:150 - Disposal of Completion Fluids
Completion fluids fall under the definition of solid non-hazardous waste. Temporary storage of these fluids is regulated as a solid waste permit-by-rule. Permit-by-rule sites do not need to submit any paperwork to the Division, but do need to comply with the environmental performance standards. Disposal of such waste is not covered by a permit-by-rule, and the applicable regulations depend on the disposal method to be employed. In order to dispose of the waste at the site by applying it to the land, a permit shall be obtained. The waste can be hauled off-site and disposed of in a permitted solid waste landfill, as long as it is allowed under the permit for that landfill.

http://www.lrc.ky.gov/kar/401/005/090.htm

Louisiana
§307. Pit Classification, Standards, and Operational
B. Reserve pits 4. Pits shall be emptied of fluids in a manner compatible with all applicable regulations, and closed in accordance with §311 and §313 within six months of completion of drilling or work over operations.

http://dnr.louisiana.gov/title43/43v19.pdf

Michigan
R 324.407 Drilling mud pits. Rule 407. The drilling mud pit shall be carefully encapsulated and buried as soon as practical after drilling completion, but not more than 6 months after drilling completion.

http://www.deq.state.mi.us/documents/deq-ogs-land-fuelsmineral-oilandgas-regs.pdf

Montana

36.22.1005 DRILLING WASTE DISPOSAL AND SURFACE RESTORATION

(1) The operator of a drilling well must contain and dispose of all solid waste and produced fluids that accumulate during drilling operations so as not to degrade surface water, groundwater, or cause harm to soils. Said waste and fluids must be disposed of in accordance with all applicable local, state and federal laws and regulations.

(2) When a salt-based or oil-based drilling fluid is used to drill a well located within a floodplain, as defined by ARM 36.15.101, or in irrigated cropland, drilling waste and produced fluids that accumulate during drilling operations must be disposed of off-site in a manner allowed by local, state, and federal laws and regulations unless an alternative on-site disposal method is approved in writing by the board administrator.

(3) The operator of a drilling well must construct, close, and restore any reserve pits in a manner that will prevent harm to the soil and will not degrade surface waters or groundwater. When a salt-based or oil-based drilling fluid is used, the reserve pit must be lined with a synthetic liner approved by the board administrator.

(4) **Within 10 days after the cessation of drilling or completion operations, all hydrocarbons must be removed from earthen pits used in association with drilling or completion operations or such pits must be fenced, screened, and netted**. Such pits that contain water with more than 15,000 parts per million total dissolved solids or salt-based drilling fluids must be fenced within 90 days after the cessation of drilling and completion operations.

(5) Earthen pits used in association with drilling and completion operations must not be used for the disposal of any additional fluids or materials after the cessation of drilling and completion operations.

(6) All earthen pits used in association with drilling and completion operations must be closed and the surface restored according to board specifications **within one year after the cessation of drilling operations**. Upon written application by the operator, an exception to the one-year pit closure requirement may be granted in writing by the board administrator upon a showing that:

> (a) no dumping or disposal of waste or fluids in the pit will occur; and
> (b) delayed closure of the pit will not present a risk of contamination to soils or water or a hazard to animals or persons.

http://data.opi.mt.gov/bills/mca_toc/82.htm

Nebraska

012.14 All pits shall be backfilled within one year after completion of drilling operations.

022.12A All pits or ponds used to retain produced water shall:

- Be constructed in cut material or at least fifty (50) percent below original ground level.
- Be lined with a material compatible with the waste contained.

- Not be located in a natural drainage and shall be constructed above the seasonal high water table.
- Be bermed or diked and shall have at least two (2) feet of freeboard between the normal operating level of the water in the pit and the top of the banks, dikes or berms.
- Be fenced, screened, or netted to prevent access by livestock, wildlife and migratory birds if free oil is likely to be discharged to the pits.

http://www.nogcc.ne.gov/NOGCCrulesstatutesindex.htm

Nevada

NAC 522.350 Open reservoirs. Oil or the waste from an oil field may not be stored or retained in unlined pits in the ground or open receptacles without the approval of the division. [Div. of Mineral Res., § 407, eff. 12-20-79]—(NAC A by Dep't of Minerals, 7-22-87)

NAC 522.255 Collecting pits. 1. No operator who conducts oil or gas development and production may use unlined collecting pits for storage and evaporation of brines from the oil field. The division may approve the use of impervious collecting pits in conjunction with approved operations for disposal of salt water. 2. The provisions of subsection 1 do not apply to burning pits which are used exclusively for the burning of the accumulated waste from the bottom of a tank. [Div. of Mineral Res., § 200 subsec. 3, eff. 12-20-79]—(NAC A by Dep't of Minerals, 7-22-87)

http://www.leg.state.nv.us/NAC/NAC-522.html

New Mexico

19.15.17.11 DESIGN AND CONSTRUCTION SPECIFICATIONS:

E. Netting. The operator shall ensure that a permanent pit or a permanent open top tank is screened, netted or otherwise rendered non-hazardous to wildlife, including migratory birds. Where netting or screening is not feasible, the operator shall on a monthly basis inspect for, and within 30 days of discovery, report discovery of dead migratory birds or other wildlife to the appropriate wildlife agency and to the appropriate division district office in order to facilitate assessment and implementation of measures to prevent incidents from reoccurring.

19.15.17.12 OPERATIONAL REQUIREMENTS

(4) The operator shall remove all free liquids from a temporary pit within 30 days from the date that the operator releases the drilling or workover rig.

19.15.2.50 PITS AND BELOW-GRADE TANKS

C. Design, construction, and operational standards.

(1) In general. Pits, sumps and below-grade tanks shall be designed, constructed and operated so as to contain liquids and solids to prevent contamination of fresh water and protect public health and the environment.

(2) Special requirements for pits.

(e) Disposal or storage pits. No measurable or visible layer of oil may be allowed to accumulate or remain anywhere on the surface of any pit. Spray evaporation systems

shall be operated such that all spray-borne suspended or dissolved solids remain within the perimeter of the pond's lined portion.
(f) Fencing and netting. All pits shall be fenced or enclosed to prevent access by livestock, and fences shall be maintained in good repair. Active drilling or workover pits may have a portion of the pit unfenced to facilitate operations. In issuing a permit, the division may impose additional fencing requirements for protection of wildlife in particular areas. All tanks exceeding 16 feet in diameter, exposed pits, and ponds shall be screened, netted, covered, or otherwise rendered non-hazardous to migratory birds. Drilling and workover pits are exempt from the netting requirement. Immediately after cessation of these operations such pits shall have any visible or measurable layer of oil removed from the surface. Upon written application, the division may grant an exception to screening, netting, or covering requirements upon a showing that an alternative method will adequately protect migratory birds or that the tank or pit is not hazardous to migratory birds.

F. Closure and restoration.
(1) Closure. Except as otherwise specified in Section 50 of 19.15.2 NMAC, a pit or below-grade tank shall be properly closed within six months after cessation of use. As

http://www.emnrd.state.nm.us/OCD/documents/RULEBOOK060328_002.pdf

New York
Part 554: Drilling Practices and Reports (Statutory authority: Environmental Conservation Law, §§ 23-0301, 23-0305[8])
§554.1 Prevention of pollution and migration
(c)(3) Storage of brine, salt water or other polluting fluids in such watertight tanks or earthen pits, prior to disposal, shall be for a maximum of 45 days after cessation of drilling operations, unless the department approves an extension based on circumstances beyond the operator's control.

§556.4 Safety
(a) Oil shall not be produced, stored or retained in earthen reservoirs.

http://www.dec.ny.gov/energy/1630.html

North Dakota
43-02-03-19. RESERVE PIT FOR DRILLING MUD AND DRILL CUTTINGS - RECLAMATION OF SURFACE. A reserve pit may be utilized to contain solids and fluids used and generated during well drilling and completion operations, providing the pit can be constructed, used and reclaimed in a manner that will prevent pollution of the land surface and freshwaters. In special circumstances, the director may prohibit construction of a reserve pit or may impose more stringent pit reclamation requirements. Under no circumstances shall reserve pits be used for disposal, dumping, or storage of fluids, wastes, and debris other than drill cuttings and fluids used or recovered while drilling and completing the well. Reserve pits shall not be located in, or hazardously near, bodies of water, nor shall they block natural drainages.

When required by the director, the reserve pit or site or appropriate parts thereof must be fenced.

1. Within a reasonable time, but not more than one year, after the completion of a well, the reserve pit shall be reclaimed. All pit water and oil on the pit must be removed prior to reclamation. Drilling waste should be encapsulated in the pit and covered with at least four feet [1.22 meters] of backfill and topsoil and surface sloped, when practicable, to promote surface drainage away from the reclaimed pit area.

43-02-03-19.1. FENCING, SCREENING, AND NETTING OF PITS. All open pits and ponds which contain saltwater must be fenced. All pits and ponds which contain oil must be fenced, screened, and netted. This is not to be construed as requiring the fencing, screening, or netting of a reserve pit or other earthen pit used solely for drilling, completing, recompleting, or plugging unless such pit is not reclaimed in excess of ninety days after completion of the operation.

History: Effective May 1, 1992.

https://www.dmr.nd.gov/oilgas/rules/rulebook.pdf

Ohio

[1509.07.2] 1509.072. Well owner's duty to restore disturbed land surface; waiver; extension.

No oil or gas well owner or agent of an oil or gas well owner shall fail to restore the land surface within the area disturbed in siting, drilling, completing, and producing the well as required in this section.

(A) Within five months after the date upon which the surface drilling of a well is commenced, the owner or the owner's agent, in accordance with the restoration plan filed under division (A)(10) of section 1509.06 of the Revised Code, shall fill all the pits for containing brine, other waste substances resulting, obtained, or produced in connection with exploration or drilling for, or production of, oil or gas, or oil that are not required by other state or federal law or regulation, and remove all concrete bases, drilling supplies, and drilling equipment.

http://www.dnr.state.oh.us/Portals/11/publications/pdf/oil%20and%20gas%20laws%20and%20rules.pdf

Oklahoma

165:10-7-16, Use of non-commercial pits

(B) The protection of migratory birds shall be the responsibility of the operator. Therefore, the Conservation Division recommends that to prevent the loss of birds, oil be removed or the surface area covered by the oil be protected from access to birds [See Advisory Notice 165: 10- 7-3(c)] .

(A) Any Category 1A, 1B, or 2 reserve/circulation pit, either on-site or off-site, shall be closed within twelve months after drilling operations cease.

(B) Any Category 3 (oil-based) reserve/circulation pit, either on-site or off-site, shall be closed within 6 months after drilling operations cease.

(C) Any Category 4 pit shall have closure procedures commenced within 30 days and completed within 90 days after drilling operations cease.

http://www.occ.state.ok.us/Divisions/GC/OCCRULES/permrules/Ch%2010%20Oil%20and%20Gas%20Conservation%20Rules%20eff%20July%2011%202008.pdf

Oregon

632-010-0140 - Reserve Pits or Sumps

Materials and fluids or any fluid necessary to the drilling, production, or other operations by the permittee shall be discharged or placed in pits and sumps approved by the department and the State Department of Environmental Quality. The operator shall provide pits, sumps, or tanks of adequate capacity and design to retain all materials. In no event shall the contents of a pit or sump be allowed to:

(1) Contaminate streams, artificial canals or waterways, groundwaters, lakes, or rivers.

(2) Adversely affect the environment, including but not limited to, persons, plants, fish, and wildlife and their populations.

(3) When no longer needed and within one year of completion, suspension of abandonment, fluid in pits and sumps shall be disposed of in a manner approved by the Department of Environmental Quality and the sumps filled and covered and the premises reclaimed. The restoration need not be done if arrangements are made with the surface owner to leave the site suitable for beneficial subsequent use. The permittee shall notify the department to inspect the site reclamation

Stat. Auth.: ORS 520
Stats. Implemented: ORS 520.095

http://arcweb.sos.state.or.us/rules/OARS_600/OAR_632/632_010.html

Pennsylvania

§ 78.56. Pits and tanks for temporary containment.

(a) Except as provided in § 78.60(b) and 78.61(b) (relating to discharge requirements; and disposal of drill cuttings), the operator shall contain pollutional substances and wastes from the drilling, altering, completing, recompleting, servicing and plugging the well, including brines, drill cuttings, drilling muds, oils, stimulation fluids, well treatment and servicing fluids, plugging and drilling fluids other than gases in a pit, tank or series of pits and tanks.

(d) Unless a permit under The Clean Streams Law (35 P. S. § § 691.1—691.1001) or approval under § 78.57 or § 78.58 (relating to control, storage and disposal of production fluids; and existing pits used for the control, storage and disposal of production fluids) has been obtained for the pit, the owner or operator shall remove or fill the pit within 9 months after completion of drilling, or in accordance with the extension granted by the Department under section 206(g) of the act (58 P. S. § 601.206(g)). Pits used during servicing, plugging and recompleting the well shall be removed or filled within 90 days of construction.

http://www.dep.state.pa.us/dep/deputate/minres/oilgas/laws&regulations.htm

South Dakota

74:10:03:13. Pit construction and reclamation. All pits used for storage of exploration and production wastes must be constructed, maintained, and reclaimed so as to prevent contamination of soil and all waters of the state. Under no circumstances may these pits be used for disposal, dumping, or storage of solid or hazardous wastes, and other debris not commonly used in these operations.

(2) Pit reclamation procedures:

(a) Within one year of site abandonment the pit must be reclaimed in a manner approved by the secretary that will prevent ground water or surface water contamination. If conditions that prevent reclamation within one year exist, a six-month extension may be granted by the secretary.

74:10:05:15.01. Pits to be constructed and operated to protect certain birds and other species. Any permanent or semipermanent pit used for the production of oil or gas must be constructed and operated to protect migratory birds and state and federal threatened, endangered, or protected species.

74:10:05:11. Oil storage in open receptacles prohibited -- Fire walls required on oil tanks. Oil may not be stored or retained in earthen reservoirs or in open receptacles.

http://legis.state.sd.us/rules/DisplayRule.aspx?Rule=74:10

Tennessee

1040-2-6-.04 ENVIRONMENTAL PROTECTION All oil and gas operations shall be conducted in a manner that will prevent or mitigate adverse environmental impacts such as soil erosion and water pollution. All areas disturbed by the operations, including access roads, shall be reclaimed as prescribed in rule 1040-2-9-.05.

1040-2-9-.05 SURFACE RECLAMATION.

(1) Abandonment of well sites, oil or gas pipeline right-of-way, storage facility sites, and access roads.

(a) Except for active work areas, the operator shall drain and fill all surface pits that are not needed for production purposes, and shall grade and stabilize the well location and location road within thirty (30) days of the initial disturbance, in order to minimize surface run-off and prevent excessive erosion and sedimentation. All drilling supplies and equipment, trash, discarded materials and other refuse not contained and covered in the reclaimed pits shall be removed from the site. Temporary vegetative cover shall then be established on all graded areas.

(b) Within thirty (30) days of the plugging and abandonment of any well, the operator shall remove all production and storage structure, supplies and equipment, any oil, salt water and debris, fill any remaining excavations, and grade any remaining disturbed areas, including access roads.

http://www.state.tn.us/sos/rules/1040/1040-02/1040-02.htm

<u>Texas</u>

RULE §3.22 Protection of Birds

(b) An operator must screen, net, cover, or otherwise render harmless to birds the following categories of open-top tanks and pits associated with the exploration, development, and production of oil and gas, including transportation of oil and gas by pipeline:

(1) open-top storage tanks that are eight feet or greater in diameter and contain a continuous or frequent surface film or accumulation of oil; however, temporary, portable storage tanks that are used to hold fluids during drilling operations, workovers, or well tests are exempt;

(2) skimming pits as defined in §3.8 of this title (relating to Water Protection) (Statewide Rule 8); and

(3) collecting pits as defined in §3.8 of this title (relating to Water Protection) that are used as skimming pits.

(c) If the commission finds a surface film or accumulation of oil in any other pit regulated under §3.8 of this title (relating to Water Protection), the commission will instruct the operator to remove the oil. If the operator fails to remove the oil from the pit in accordance with the commission's instructions or if the commission finds a surface film or accumulation of oil in the pit again within a 12-month period, the commission will require the operator to screen, net, cover, or otherwise render the pit harmless to birds.

RULE §3.8 Water Protection - (iii) The director may require that a person who uses or maintains a reserve pit, mud circulation pit, fresh makeup water pit, fresh mining water pit, completion/workover pit, basic sediment pit, flare pit, or water condensate pit backfill the pit sooner than the time prescribed by clause (i) of this subparagraph if the director determines that oil and gas wastes or oil field fluids are likely to escape from the pit or that the pit is being used for improper storage or disposal of oil and gas wastes or oil field fluids.

(iv) Prior to backfilling any reserve pit, mud circulation pit, completion/workover pit, basic sediment pit, flare pit, or water condensate pit whose use or maintenance is authorized by this paragraph, the person maintaining or using the pit shall, in a permitted manner or in a manner authorized by paragraph (3) of this subsection, dispose of all oil and gas wastes which are in the pit.

(G) Backfill requirements.

(i) A person who maintains or uses a reserve pit, mud circulation pit, fresh makeup water pit, fresh mining water pit, completion/workover pit, basic sediment pit, flare pit, or water condensate pit shall dewater, backfill, and compact the pit according to the following schedule.

(I) Reserve pits and mud circulation pits which contain fluids with a chloride concentration of 6,100 mg/liter or less and fresh makeup water pits shall be dewatered, backfilled, and compacted within one year of cessation of drilling operations.

(II) Reserve pits and mud circulation pits which contain fluids with a chloride concentration in excess of 6,100 mg/liter shall be dewatered within 30 days and backfilled and compacted within one year of cessation of drilling operations.

(III) All completion/workover pits used when completing a well shall be dewatered within 30 days and backfilled and compacted within 120 days of well completion. All completion/workover pits used when working over a well shall be dewatered within 30 days and backfilled and compacted within 120 days of completion of workover operations.

http://www.rrc.state.tx.us/rules/rule.php

Virginia

4 VAC 25-150-300. Pits.

A. General requirements.

1. Pits are to be temporary in nature and are to be reclaimed when the operations using the pit are complete.
2. Pits may not be used as erosion and sediment control structures or stormwater management structures, and surface drainage may not be directed into a pit.
3. Pits shall have a properly installed and maintained liner or liners made of 10mil or thicker high-density polyethylene or its equivalent.

C. 3. At the conclusion of drilling and completion operations or after a dry hole, well or corehole has been plugged, the pit shall be drained in a controlled manner and the fluids disposed of in accordance with 4 VAC 25-150-420. If the pit is to be used for disposal of solids, then the standards of 4 VAC 25-150-430 shall be met.

4 VAC 25-150-420. Disposal of pit and produced fluids.

A. Applicability. All fluids from a well, pipeline or corehole shall be handled in a properly constructed pit, tank or other type of container approved by the director.
A permittee shall not dispose of fluids from a well, pipeline or corehole until the director has approved the permittee's plan for permanent disposal of the fluids. Temporary storage of pit or produced fluids is allowed with the approval of the director. Other fluids shall be disposed of in accordance with the operations plan approved by the director.

B. Application and plan. The permittee shall submit an application for either on-site or off-site permanent disposal of fluids on a form prescribed by the director. Maps and a narrative describing the method to be used for permanent disposal of fluids must accompany the application if the permittee proposes to land apply any fluids on the permitted site. The application, maps, and narrative shall become part of the permittee's operations plan.

C. Removal of free fluids. Fluids shall be removed from the pit to the extent practical so as to leave no free fluids. In the event that there are no free fluids for removal, the permittee shall report this on the form provided by the director.

http://leg1.state.va.us/000/reg/TOC04025.HTM#C0150

Utah

R649-1-1. Definitions. “Disposal Pit" means a lined or unlined pit approved for the disposal and/or storage of E and P Wastes.

R649-3-15. Pollution and Surface Damage Control.

1. The operator shall take all reasonable precautions to avoid polluting lands, streams, reservoirs, natural drainage ways, and underground water.
1.2. At a minimum, the owner or operator shall:
1.2.1. Take reasonable steps to prevent and shall remove accumulations of oil or other materials deemed to be fire hazards from the vicinity of well locations, lease tanks and pits.
1.2.4.1. The use of crude or produced water storage tanks without tops is strictly prohibited except during well testing operations.
1.2.5. Catch leaks and drips, contain spills, and cleanup promptly.
1.2.6. Waste reduction and recycling should be practiced in order to help reduce disposal volumes.
1.2.7. Produced water, tank bottoms and other miscellaneous waste should be disposed of in a manner that is in compliance with these rules and other state, federal, or local regulations or ordinances.

R649-3-16. Reserve Pits and Other On-site Pits.

1. Small onsite oil field pits including, but not limited to, reserve pits, emergency pits, workover and completion pits, storage pits, pipeline drip pits, and sumps shall be located and constructed in such a manner as to contain fluids and not cause pollution of waters and soils. They shall be located and constructed according to the Division guidelines for onsite pits.

3. Following drilling and completion of the well the reserve pit shall be closed within one year, unless permission is granted by the Division for a longer period.

R649-9-3. Permitting of Disposal Pits.

2.3.6. The pit shall be fenced and maintained to prevent access by livestock, wildlife and unauthorized personnel and if required, equipped with flagging or netting to deter entry by birds and waterfowl.

http://oilgas.ogm.utah.gov/Rules/Rules.htm

West Virginia

'35-4-16. Reclamation.

16.4.h. All drilling pits and alternative overflow prevention facilities shall be constructed, maintained, and reclaimed so as not to be left in such condition as to constitute a hazard or to prevent use of the surface for agricultural purposes after the expiration of the six (6) month or extended period for reclamation prescribed by W. Va. Code '22-6-30.

http://www.wvsos.com/csr/verify.asp?TitleSeries=35-04

Wyoming

Chapter 4, Section 1. Pollution and Surface Damage

(bb) Reserve pits shall be completely fenced and, if oil or other harmful substances are present, netted or otherwise secured at the time the rig substructure has been moved from the location in a manner that avoids the loss of wildlife, domestic animals, or migratory birds. Because of the same concerns, produced water pits must be fenced and, if oil or other harmful substances are present, netted or secured in such a manner as to provide protection to wildlife, domestic animals, or migratory birds. The Commission recommends netting as the preferred means of securing pits.

(dd) All retaining pits shall be kept reasonably free of surface accumulations of oil and other liquid hydrocarbon substances and shall be cleaned within ten (10) days after discovery of the accumulation by the owner or notice from the Supervisor.

(ll) The Commission specifically prohibits the use of dispersants, wetting agents, surface reduction agents, surfactants, or other chemicals that destroy, remove, or reduce the fluid seal of a reserve pit and allow the fluids contained therein to seep, drain, or percolate into the soil underlying the pit.

(qq) **Reclamation**. Reclamation of unused production pits or any other temporary retaining pits, including reserve pits, shall be completed in as timely a manner as climatic conditions allow. Production pit areas and reserve pits will be reclaimed no later than one (1) year after the date of last use unless the Supervisor grants an administrative variance for just cause.

http://soswy.state.wy.us/RULES/rules/6855.pdf

Exhibit 30.11

This exhibit was not previously submitted in November 2023

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Environmental Contamination and Toxicology

Exposure and Effects of Oilfield Brine Discharges on Western Sandpipers (*Calidris mauri*) in Nueces Bay, Texas

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Discharge of oilfield brines into fresh and estuarine waters is a common disposal practice in Texas. Petroleum crude oil (PCO) extraction from underground stores includes the removal of a significant amount of water along with the oil. Several methods may be used to separate the oil and water fractions, including tank batteries, heat separation, and skimming ponds. Disposal of the resultant produced water (oilfield brine) may be accomplished by deep-well injection or discharge to surface waters. In Texas, an estimated 766,000 barrels of oilfield brine were discharged daily into tidal waters in 1979 (Liebow et al. 1980). The maximum concentration for oil and grease in these discharges permitted by the Texas Railroad Commission is 25 ppm. Several studies have shown that oilfield brines are toxic to a wide range of marine life (Simmons *Texas Railroad Comm. Oil and Gas Docket No. 2 and 4-60, Nov. 4, 1970*; Spears *Texas Railroad Comm., Oil and Gas Docket 62099, July 26, 1972*; Andreasen and Spears 1983; Boelter et al. 1992), yet little is known about their effects on birds and mammals.

Exposure to petroleum in oilfield wastes could evoke toxicological effects in some waterbird species. Avian responses to PCO exposure are highly variable, including cessation of growth, osmoregulatory impairment, endocrine dysfunction, hemolytic anemia, altered blood chemistry, cytochrome P450 induction, reduced reproductive success, and mortality (Holmes 1984; Albers 1991; Leighton 1991). Oilfield brine discharges may soon be the largest and most pervasive source of contaminants entering Texas estuaries. Migratory and resident birds feeding in the vicinity of discharge sites may be ingesting food items contaminated with petroleum hydrocarbons, heavy metals and salts in sufficient quantities to evoke toxicity. The present study of wintering western sandpipers (*Calidris mauri*) that feed and roost near discharge sites sought to examine oilfield brine exposure and effects through quantification of contaminant burdens, morphological characteristics, and cytochrome P450-associated monooxygenase activities.

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MATERIALS AND METHODS

Whites Point ($27^{o}47'N$, $97^{o}35'W$), on the north shore of Nueces Bay, near Corpus Christi, Texas, is a multiple oilfield brine discharge area consisting of nine wastewater disposal sites located along a 3 km stretch of marsh, mudflat, and brackish water ponds. Bolivar Flats ($29^{o}19'N$, $94^{o}55'W$), located on the Bolivar peninsula east of Galveston Island, was selected as a presumably uncontaminated reference site. Whites Point is located 190 km southwest of Bolivar Flats.

Western sandpipers, a winter resident at both sites, were collected by shotgun in March 1990, several months after their migratory arrival. Immediately after collection, whole body and liver weight were determined. Livers were blotted free of blood, minced, placed in storage vials containing glycerol, frozen in liquid nitrogen, and stored at $-70^{o}C$ for subsequent biochemical analysis. Bill length was measured, and carcasses were prepared for contaminant analysis by removing the feathers, bill, feet, wing tips and gastrointestinal tract. When stomach contents were available, they were pooled to obtain sufficient mass for a composite sample from each site.

Pooled stomach contents and carcasses were analyzed for 13 aliphatic and 14 aromatic hydrocarbons (Belisle et al. 1981). The lower limit of detection for aliphatic and aromatic hydrocarbons was 0.01 ppm. In addition, half of the carcasses from each site were analyzed for 21 organochlorine pesticides and metabolites, and total polychlorinated biphenyls (PCBs) concentrations (Cromartie et al. 1975). The lower limit of detection was 0.01 ppm for organochlorine pesticides and 0.05 ppm for PCBs.

Cytochrome P450-associated monooxygenase activity of liver samples was determined as recently described in detail by Rattner et al. (1993). Samples were thawed, homogenized in phosphate buffer, and a microsomal pellet was prepared by differential centrifugation. The pellet was resuspended and assayed for protein concentration. Arylhydrocarbon hydroxylase (AHH) activity was measured by radio-enzymatic determination of total hydroxylation products formed by the metabolism of ^{3}H-benzo[*a*]pyrene. Activity of AHH is expressed as pmol of total metabolites formed/min/mg microsomal protein. The activities of benzyloxyresorufin-*O*-dealkylase (BROD), ethoxy-coumarin-*O*-dealkylase (ECOD), and ethoxyresorufin-*O*-dealkylase (EROD) and pentoxyresorufin-*O*-dealkylase (PROD) were determined by the rate of formation of fluorescent product. Dealkylase enzyme activity is expressed as pmol or nmol product/min/mg microsomal protein.

Contaminant burdens, morphological characteristics, and activities of monooxygenases were tested for homogeneity of variance using the F_{max} test, and some variables were $\log_{10}$ transformed to stabilize variances. One-half the lower limit of detection was used for statistical analyses for samples without detectable pristane, phytane, n-heptadecane and octadecane, and PCB burdens. In all cases, at least one half of the samples had detectable contaminant levels. Sites were compared using Student's t-test (two-tailed). Linear relationships among contaminant burdens and biological parameters were examined using Pearson product-moment correlation.

RESULTS AND DISCUSSION

The concentration of total aliphatic petroleum hydrocarbons in pooled stomach contents of sandpipers was relatively similar at reference and discharge sites (1.05 and 0.71 ppm, respectively), but total aromatic petroleum hydrocarbon concentration in stomach contents of birds collected at the discharge site (1.42 ppm) was over tenfold greater than at the reference site (0.10 ppm). Total detectable aliphatics in carcasses did not differ between sites (Table 1), although the concentration of pristane and the ratio of pristane:n-heptadecane were at least fivefold greater ($p < 0.01$) at the discharge site. Pristane (a branch chain hydrocarbon often abundant in pollutant oils) and its ratio to n-heptadecane (predominantly of biological origin) were greater at the discharge site. The apparent accumulation of pristane and its elevated ratio to n-heptadecane are indicative of chronic petroleum hydrocarbon exposure (Giger et al. 1974; Hall and Coon 1988). Aromatic petroleum hydrocarbons were rarely detected in carcasses, and when present, concentrations were 0.02 ppm or less. Based on a six to seven month winter residency at this location (King *unpub. data*), the moderate concentration of petroleum hydrocarbons in stomach contents, and the limited accumulation of select hydrocarbons in carcasses, overall exposure appears to be modest compared to that encountered following an oil spill (Albers 1991).

Concentrations of organochlorine contaminants were relatively low at both sites (Table 1). Of the 10 carcasses analyzed from the discharge site, all contained detectable levels of p,p'-DDE (≤ 0.25 ppm) and PCBs (≤ 0.98 ppm), 7 carcasses contained both oxychlordane (0.01) and heptachlor (≤ 0.05 ppm), 3 contained *trans*-nonachlor (0.01 ppm), and 1 contained dieldrin (0.01 ppm). Of the 5 carcasses analyzed from the reference site, all contained detectable levels of p,p'-DDE (≤ 0.06 ppm), 4 contained PCBs (≤ 0.80 ppm), 2 contained both oxychlordane (0.01) and heptachlor (0.01 ppm), and 1 contained dieldrin (0.01 ppm). No other organochlorine compounds were detected in the samples. Organochlorine concentrations were below those known to cause avian mortality or reproductive problems and comparable to background levels found in previous studies (White et al. 1980; White et al. 1983).

Body weight and bill length were similar between sites, although liver weight and liver:body weight ratio were significantly lower (>25% reduction) at the discharge site ($p < 0.01$; Table 2). Exposure to PCO is often accompanied by hepatic hypertrophy (Miller et al. 1978; Gorsline and Holmes 1981), although reduced liver weight has been observed in mallards (*Anas platyrhynchos*) following chronic low level dietary exposure (0.5% South Louisiana crude oil)(Gorsline and Holmes 1981). In the present study, liver weight was inversely correlated with the pristane:n-heptadecane ratio ($r^2=-0.37$; $P<0.05$), consistent with chronic low level exposure.

Table 1. Carcass contaminant burdens of western sandpipers collected at reference and oilfield brine discharge sites[a].

	Bolivar Flats Reference Site N = 11[b]	Whites Point Discharge Site N = 19[b]
Total aliphatics (ppm)	1.7 (1.0 - 4.4)	1.8 (0.02 - 2.0)
Pristane (ppm)	0.07 (ND[c] - 0.44)	0.40* (0.02 - 2.0)
Pristane:n-heptadecane ratio	0.312 (0.003 - 3.1)	2.33* (0.087 - 18.9)
Total organochlorine pesticides and metabolites (ppm)	0.05 (0.03 - 0.07) N = 5	0.09 (0.02 - 0.27) N = 10
Total PCBs (ppm)	0.36 (ND - 0.80) N = 5	0.53 (0.29 - 0.98) N = 10

[a]Values presented are geometric mean and (range); concentrations are reported on wet-weight basis.
[b]Unless otherwise noted.
[c]ND = not detected.
*Significantly different ($p < 0.01$) by Student's t-test.

Activities of AHH, BROD (log transformed), ECOD, EROD, and PROD (expressed per mg of microsomal protein) were similar ($p > 0.05$) in birds collected at both locations (Table 2). Inspection of monooxygenase activities of individual birds from the discharge site revealed that activity rarely exceeded two standard deviations of the reference site mean (1 of 19 observations for AHH, BROD, ECOD and PROD; 2 of 19 observations for EROD). Monooxygenases were also examined in terms of activity per gram liver, total activity per liver, and activity per gram body weight. No statistical differences between sites were detected, with the exception of slightly greater PROD activity per liver and per g body weight at the reference site (mean units/liver: 720.8 versus 415.3; mean units/g body weight: 29.1 versus 17.1). These data strongly suggest that hepatic cytochrome P450 is not induced in birds residing at or near the oilfield brine discharge site.

Induction of cytochrome P450 and associated monooxygenase activity has been used extensively as a biomarker of exposure to some organic pollutants in wildlife (Rattner et al. 1989, 1993). PCO induces monooxygenase activity in a variety of avian species (Miller et al. 1978; Gorsline and Holmes 1981; Peakall et al. 1987, 1989), and

Table 2. Morphological indices and hepatic microsomal monooxygenase activities of western sandpipers collected from reference and oilfield brine discharge sites[a].

	Bolivar Flats Reference Site	Whites Point Discharge Site
	N = 11	N = 19
Body weight (g)	24.7 ± 0.4 (22.6 - 26.4)	23.9 ± 0.5 (20.9 - 27.5)
Bill length (mm)[b]	23.6 ± 0.6 (21.0 - 26.0)	23.4 ± 0.5 (21.5 - 28.0)
Liver weight (g)	1.23 ± 0.07 (0.9 - 1.8)	0.87 ± 0.06* (0.5 - 1.7)
Liver:body weight ratio (g/100 g)	4.99 ± 0.34 (3.41 - 7.89)	3.63 ± 0.23* (2.39 - 7.20)
AHH (pmol/min/mg)	1041 ± 81 (435 - 1332)	970 ± 97 (524 - 2347)
BROD (pmol/min/mg)	75.3 ± 16.0 (0.4 - 149)	134.5 ± 35.4 (35 - 730)
ECOD (nmol/min/mg)	1.7 ± 0.1 (0.8 - 2.5)	1.8 ± 0.1 (0.9 - 3.1)
EROD (pmol/min/mg)	1119.8 ± 222.3 (394.4 - 2760)	719.0 ± 105.2 (196.3 - 1802)
PROD (pmol/min/mg)	72.1 ± 11.2 (2.5 - 114)	49.9 ± 5.5 (24.4 - 106)

[a]Values presented are mean ± S.E and (range).
[b]N=8 for reference site and N=18 for discharge site.
*Significantly different ($p < 0.01$) by Student's t-test.

induction seems to be preferentially linked to the aromatic fraction (Walters et al., 1987; Peakall et al. 1989). The absence of elevated hepatic microsomal monooxygenase activity at the Whites Point discharge site suggests that despite a tenfold difference in petroleum aromatic hydrocarbon content of foods between sites, the concentrations of organic contaminants were insufficient to induce cytochrome P450. The decreases in total hepatic PROD activity and PROD activity per g body weight in sandpipers collected at the Whites Point discharge site could be simply the result of the decreased liver size. Alternatively, oilfield brine discharges near Corpus Christi contained cadmium, lead and mercury at concentrations exceeding the U.S. EPA marine chronic water quality criteria by 700, 8 and 4000 times (Pedroy Ramirez, U.S. Fish and Wildlife Service, 1983 *pers. comm.*). These metals are capable of stimulating heme oxygenase activity and thus decreasing cytochrome P450 (Maines and

Kappas 1977). Monooxygenase activities were not correlated with contaminant burdens in the present study.

In conclusion, petroleum aromatic hydrocarbon concentrations in food items, carcass aliphatic contaminant burdens and reduced liver weight of sandpipers collected at the oilfield discharge site suggest chronic exposure to petroleum hydrocarbons. Some avian species are sensitive to PCO, whereas others can ingest substantial quantities without deleterious effect (Holmes 1984). Ingested contaminants were not of sufficient quantity or potency to induce cytochrome P450-associated monooxygenase activity. These data suggest that adult sandpipers may be relatively tolerant to petroleum hydrocarbons typically contained in oilfield brine discharges. Furthermore, because early avian life stages are particularly sensitive to these pollutants, additional studies may be warranted in waterbird species that nest and feed near these discharge sites. Future wildlife hazard assessments at oilfield brine discharge sites should also include biomarkers of metal exposure and effects.

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Exhibit 30.12

This exhibit was not previously submitted in November 2023

Mosquito Larval Habitat Mapping Using Remote Sensing and GIS: Implications of Coalbed Methane Development and West Nile Virus

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ABSTRACT Potential larval habitats of the mosquito *Culex tarsalis* (Coquillett), implicated as a primary vector of West Nile virus in Wyoming, were identified using integrated remote sensing and geographic information system (GIS) analyses. The study area is in the Powder River Basin of north central Wyoming, an area that has been undergoing a significant increase in coalbed methane gas extractions since the late 1990s. Large volumes of water are discharged, impounded, and released during the extraction of methane gas, creating aquatic habitats that have the potential to support immature mosquito development. Landsat TM and ETM+ data were initially classified into spectrally distinct water and vegetation classes, which were in turn used to identify suitable larval habitat sites. This initial habitat classification was refined using knowledge-based GIS techniques requiring spatial data layers for topography, streams, and soils to reduce the potential for overestimation of habitat. Accuracy assessment was carried out using field data and high-resolution aerial photography commensurate with one of the Landsat images. The classifier can identify likely habitat for ponds larger than 0.8 ha (2 acres) with generally satisfactory results (72.1%) with a lower detection limit of ≈0.4 ha (1 acre). Results show a 75% increase in potential larval habitats from 1999 to 2004 in the study area, primarily because of the large increase in small coalbed methane water discharge ponds. These results may facilitate mosquito abatement programs in the Powder River Basin with the potential for application throughout the state and region.

KEY WORDS *Culex tarsalis*, risk, discharge water

Accurate mapping of the spatial distribution of mosquito breeding habitats is essential for cost-effective deployment of control practices. Geospatial mapping by using remote sensing offers the potential to identify larval habitats on a large area basis to a degree that is difficult or impossible using conventional ground survey (Hayes et al. 1985, Washino and Wood 1994, Dale et al. 1998, Hay et al. 1998). The objective of this study is to assess potential larval habitats of *Culex tarsalis* (Coquillett) by using Landsat TM imagery in the Powder River Basin of northern Wyoming in an effort to establish a basis for predicting risk of exposure to West Nile virus. Mosquitoes of the genus *Culex* are the dominant disease vector and transmitter of the West Nile Virus (Hayes 1989, Goddard et al. 2002). In Wyoming, the primary vector species is *Culex tarsalis* (E.T.S., unpublished data).

Mosquito control is a critical component of the arbovirus control programs, and one of the most effective ways to control a mosquito population is to reduce its larval (breeding) habitats. Previous studies have shown benefits of using remote sensing in the identification of mosquito breeding habitats (Linthicum et al. 1987, Pope et al. 1992, Wood et al. 1992, Dale and Morris 1996, Thomson et al. 1996, Masuoka et al. 2003). However, these studies have not targeted West Nile Virus or the intermountain West and plains areas in Wyoming where West Nile Virus risk is high. Rogers et al. (2002) used AVHRR 1-km resolution data set to create a West Nile virus risk map in North America. From an operational point of view, the map resolution is too coarse to implement local control strategies and is not specific to larval habitat. With the increasing status of this emerging arbovirus, a more accurate and finer grained mapping system is necessary to aid the West Nile Virus prevention program. Landsat TM data has proven to be an excellent choice for environmental studies in past 26 yr. Landsat spectral data, particularly band 4 (infrared) and band 5 (mid-infrared) are well suited for vegetation and water content analysis, and data are collected at a scale suitable for regional and local analysis. For these reasons Landsat TM data were chosen as the base imagery for larval habitat assessment.

Since West Nile Virus arrived in New York City in 1999, it has spread across the North American continent (Enserink 2002), and by the end of 2004, the total human deaths reached 374 cases nationwide. The state of Wyoming was hit heavily in 2003 with 375 human cases, including nine deaths (CDC 2004). In addition to posing a clear threat to human health, the West Nile

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Virus poses a threat to native wildlife species. For example, the West Nile Virus is hypothesized to be responsible for the sharp decline of greater sage-grouse, *Centrocercus urophasianus*, in this region because the survival rate of this species has been reduced by 25% in recent years (Naugle et al. 2004). Of importance to potential management and control strategies in this area, the greater sage-grouse is an ecologically threatened species in the United States, and there is concern regarding the impact of the virus on sage grouse populations throughout the West (Naugle et al. 2004). At a minimum, alterations to the landscape and subsequent threats to wildlife and people indicate that monitoring and controlling the West Nile virus is a critical and potentially long-term commitment (Morse 2003) requiring a temporal and spatial strategy.

In general, *Cx. tarsalis* are small standing water species. Gravid females are attracted to water with high organic matter (Beehler and Mulla 1995) and larvae of *Cx. tarsalis* feed on organic debris in water that has a very little disturbance either in the form of wave action or flow. In a natural environment, larval habitats of *Cx. tarsalis* are often associated with vegetation growing at pond edges (Reisen 1993). More specifically, the edges of small water bodies where vegetation and other debris are concentrated are identified as larval microhabitat. Large water bodies (usually larger than 4 ha [10 acres]) that are exposed to wind and wave action, and running water such as a river or stream, are not suitable for larval development. Open waters are also unsuitable because larvae and pupae are vulnerable to predation (Laird 1988). Nutrition concentrations in open water region and running streams are generally much lower than pond edges and small standing water (Laird 1988). According to a survey conducted by Denke and Spackman (1990), the majority of mosquito-breeding habitats in Wyoming are created by human activities. In the Powder River Basin, human-made water storages, such as livestock watering ponds and discharge water ponds used in coalbed methane (CBM) development (natural gas) constitute the most likely breeding and larval habitats for *Cx. tarsalis* (Fig. 1).

CBM is a naturally occurring gas contained within unexposed coal beds. Recently strong demand makes it potentially highly profitable to extract CBM from buried coal seams. Water is a critical component in this system, because gas is held in place by water pressure. To extract methane, the water must be removed to allow the gas to flow freely from the coal, in a process referred to as "dewatering" (Nuccio 2001). The amount of water produced in this manner is considerable. Rice et al. (2000) estimated that >1.28 million barrels of water was produced each day from CBM extraction in 2000. Wyoming has witnessed a sharp increase in CBM discharge ponds associated with the development of CBM fields throughout the state, particularly the Powder River Basin in northern Wyoming because it has experienced the greatest growth in volume of discharge water and numbers of wells and ponds over the past decade (WOGCC 2005). Vast quantities of methane gas occur in association with shallow coal beds (24,000 feet in depth) that underlie the Powder River Basin in north central Wyoming. Since 1999 when it became economically feasible to tap natural gas in the Powder River Basin, ≈19,000 CBM wells have been drilled, and ≈20,000 additional wells are projected over the next decade. Total recoverable production of coproduced water in the Powder River Basin alone exceeds 5.5 million acre-feet (DOE 2002). In the study area, the majority of coproduced water is discharged onto the surface and into small detention basins, leading to an increase in small water bodies. These recent increases in ponded water are hypothesized to increase WNV risk because CBM ponds may serve as suitable habitat for larval *Cx. tarsalis.*

Materials and Methods

Data and Software. The basic research strategy was to 1) develop habitat classification techniques using historical imagery, 2) classify two images using these techniques to capture the temporal and spatial changes in habitat, 3) validate these techniques by using a combination of field observations and high resolution aerial photography.

Landsat TM images and other GIS data were obtained from the WyomingView data repository via the Wyoming Geographic Information Center download site (http://www.wygisc.uwyo.edu/clearinghouse). Three images were selected for use in this study that capture the temporal and spatial changes: 12 August 2004 (Landsat 5 TM), 14 August 2001 (Landsat 7 ETM+), and 9 August 1999 (Landsat 7 ETM+). The ETM+ images are USGS L1-T products that have been processed for radiometric, geometric, and terrain corrections. The 1999 and 2004 images serve as end members for change detection, whereas the 2001 image was classified as a separate validation data set and compared against high-resolution photography taken at approximately the same time. The TM image has been corrected for radiometric and geometric distortions. Spatial data used in the GIS portion of this research were National Elevation Dataset for Wyoming (DEM; 30-m spatial resolution), National Land Cover Dataset for Wyoming (NLCD; 30-m spatial resolution), and major hydrography features. Color infrared Digital Orthophoto Quarter Quads (DOQQs; 1-m spatial resolution acquired in July 2001) were downloaded from the Wyoming Spatial Data Clearinghouse (http://wgiac2.state.wy.us) for validation of the 2001 imagery.

An integrated raster (image classification) and vector (GIS) analysis was used to refine the identification of *Cx. tarsalis* larval habitat. Image classification was conducted using the ERDAS IMAGINE 8.7 (Leica Geosystems GIS & Mapping, LLC, Atlanta, GA). Image processing algorithms in this paper are cited at ERDAS documentation (ERDAS, Inc. 2003).

To address that suitable habitat may be defined as the junction between riparian vegetation and water, a GIS-based spatial analysis procedure was implemented in ArcGIS 9.0 (ESRI, Redlands, CA) to union

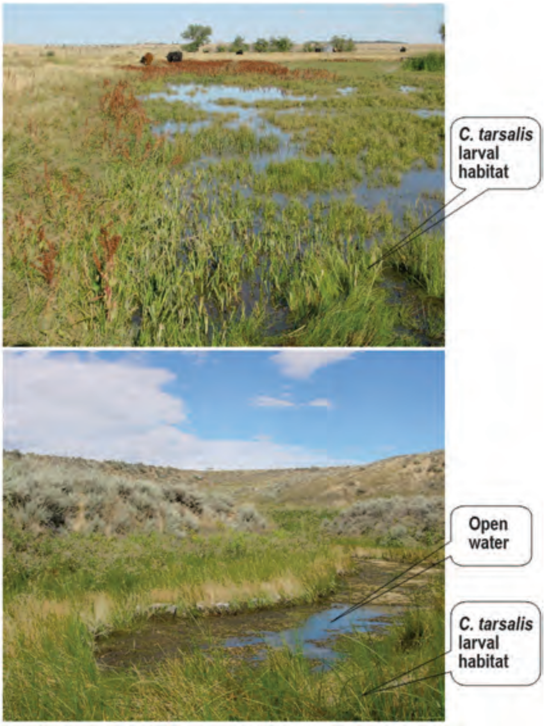

Fig. 1. Discharge pools of CBM development. The *Cx. tarsalis* larval habitat is the vegetation at the pond edges.

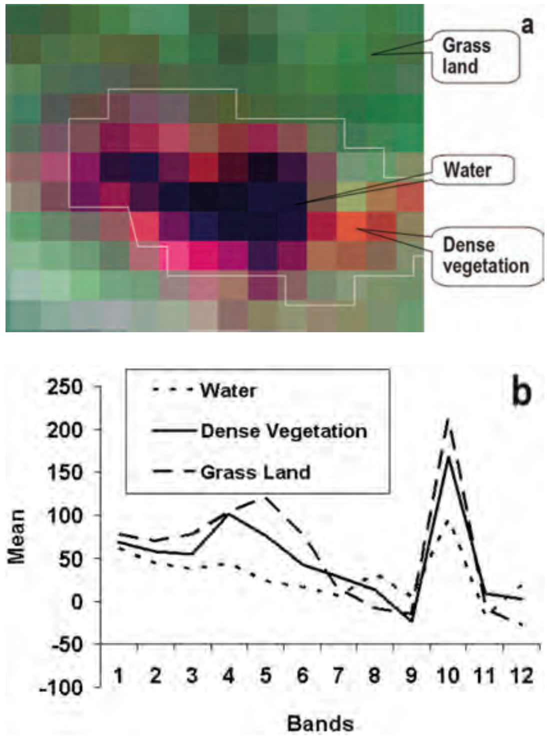

Fig. 2. (A) Typical larval habitat of *Cx. tarsalis* in the Landsat TM image (red, band 4; green, band 5; blue, band 3). The circled area is the Areas of interest. (B) Bands in spectral reflectance graph are as follows: Landsat TM, bands 1–6; NDVI*100, band 7; NDWI*100, band 8; flood index*100, band 9; Tasseled cap transformation bands 10, brightness; 11, greenness; and 12, wetness.

all dense vegetations identified from panchromatic band and any riparian vegetation located at the edges of water bodies. Union is a process of merging overlapping multiple features into a single feature. All such pixels were classified as potentially suitable habitats. Selected habitats were exported into an ArcGIS format shapefile for refinement by using GIS techniques.

Based on the factor that large water bodies and flowing streams are not suitable for larval development of *Cx. tarsalis*, pixels that spatially intersected or abutted these features were eliminated. Large open water bodies larger than 4 ha were identified using standard patch analysis. Small digitization and georectification errors may cause discontinuities between the imagery and GIS data sets, resulting in the outcome that stream lines do not always directly overlap with corresponding water and riparian classes in classified images. A 30-m buffer zone was created to ensure that pixels of major streams in the classified images intersected with their GIS-based vector counterparts. Potential habitat that intersected with the buffered major stream vector data were excluded from the final classified map.

Another potential source of error occurs where shadows from hillside or forest areas are misclassified as water; these areas were eliminated by only allowing classified habitat pixels to be present on slopes $<5°$. This approach served the dual purpose of removing areas where water is flowing due to gravity from consideration under the premise that larval habitat is dependent on stagnant or very slow-moving water.

Image Classification. From a false color composite Landsat TM image, a typical larval habitat of *Cx. tarsalis* can be recognized as a mosaic of several dark pixels (water) adjacent to red pixels (vegetation) (Fig. 2). Areas of interest (AOI) were delineated by selecting pixels in known larval-positive sites (Fig. 2). Because of limited access to the area due to private landholdings, field samples could not cover all combinations of land cover types identified in the scene. To compensate for uneven access to the study area and to create a more evenly distributed set of training data, additional areas of interest were manually selected according to field experiences and familiarity with the region. In addition to six bands of Landsat TM data, several variables that may contribute to the image classification were derived and stacked with original images. These variables are: Normalized difference vegetation index (NDVI); flooding index (FI; Philipson and Hafker 1981); Normalized Difference Water Index (NDWI; Gao 1996), and Tasseled cap transformation (Kauth and Thomas 1976, Crist and Cicone 1984).

The classification workflow is shown as Fig. 3. An unsupervised classification (Iterative Self-Organizing Data Analysis Technique; ISODATA) was used to generate four classes in the areas of interest extracted

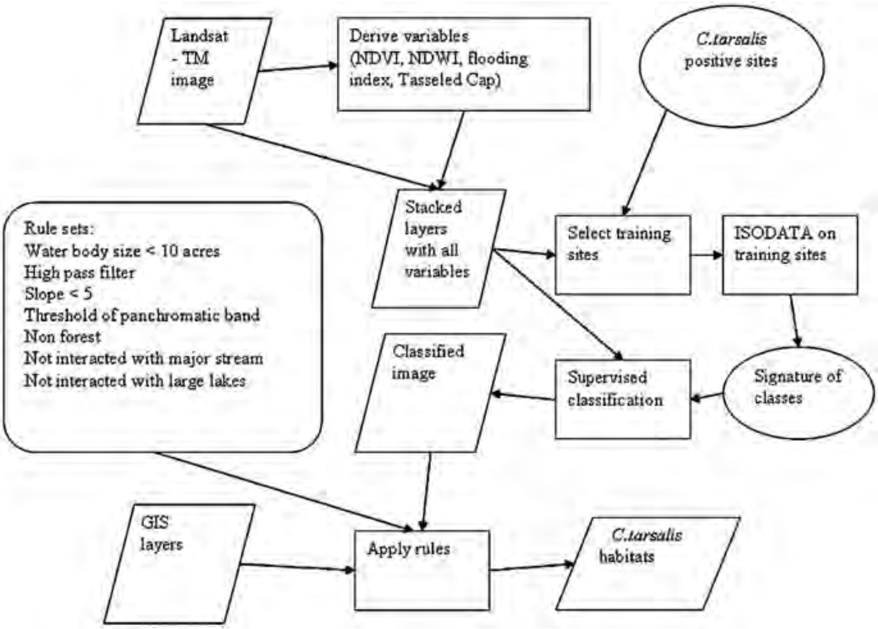

Fig. 3. Workflow of classification of *Cx. tarsalis* larval habitats.

from the positive sites from field sampling. The mean of each cluster is determined by an iterative process to meet the condition that each pixel is assigned to the class with the minimum distance (see equation). Iterations stop when the convergence threshold T, normalized percentage of pixels without change of assignment, is reached (in this case, T reached the threshold of 95% at iteration 3). A fifth class was added into the signature editor by using grassland pixels extracted from an AOI because grasslands are the dominant background vegetation type surrounding water and emergent vegetation. Using the signature generated from ISODATA, a supervised classification was conducted to classify the image. The parameter setting is as follows: nonparametric rule (parallelpiped), overlap rule (parametric rule), unclassified rule (parametric rule), and parametric rule (minimum distance). First, a candidate pixel is subjected to parallelpiped classification in which a pixel is assigned within the limits of mean ± SD of each class. Second, pixels in the overlapping region of classes or left without assignment to any class in parallelpiped classification are assigned to the closest class by using the parametric rule of minimum distance (see equation). The spectral distance from pixel *x*, *y* to the mean of class c is defined as SD_{xyc} by using the equation:

$$SD_{xyc} = \sqrt{\sum_{i=1}^{n} (\mu_{ci} - X_{xyi})^2}$$

where X_{xyi} is data file value of pixel *x*, *y* in band *i*, and μ_{ci} is mean of data file values in band *i* for the sample for class *c*.

These five classified classes were compressed into three classes: water, dense vegetations, and grasslands and shrubs. *Cx. tarsalis* larval habitat was represented as dense vegetation immediately adjacent to small water bodies. The habitats were extracted from classified images to meet these criteria. Final habitats were generated using rule based modeling according to the knowledge from experts and our field experiences.

Accuracy Assessment. A field study was undertaken in August 2004 to identify *Cx. tarsalis* larval habitats. Sampling coordinates were recorded using a geographic positioning system and transformed into a GIS data layer. Mosquito larvae were collected along pond edges by using a standard dipper. For each site, four dipping were taken every 5 m with a total distance of 100 m. Collected larvae were sorted by species at the USDA–ARS Arthropod Borne Animal Disease Research Laboratory in Laramie, WY. Sites were classified as positive if larvae of *Cx. tarsalis* were identified. Sites positive for *Cx. tarsalis* were overlaid with the image and used as training sites for the extraction of appropriate spectral signatures.

The classified result from the 14 August 2001 image was compared against the DOQQs on 1 July 2001 for an accuracy assessment. The area covered by the DOQQs is ≈171,450 ha. All small water bodies (excluding running rivers) in the DOQQs were digitized by hand as a proxy for ground truth. As noted, this area is highly dynamic due to the very rapid pace of CBM development, and the use of aerial photography serves as a static data layer that was coincident in timing with the satellite overpass. Ponds with area larger than ≈0.04 ha (≈0.1 acre) were used as the reference (equivalent to 1 pixel size in Landsat TM images, 30 by 30 m). The error matrix was computed using the final classified results and digitized ponds.

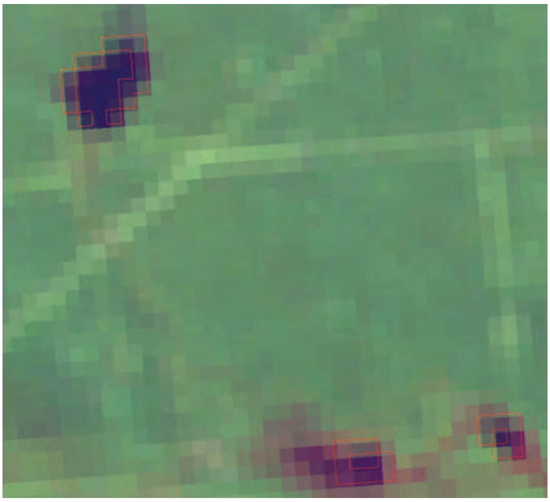

Fig. 4. Section of classified map of *Cx. tarsalis* larval habitats. The habitats are shown as the ring-shaped polygons covering the area of vegetation adjacent to small water bodies.

Results

Spectral Analysis and Interpretation of Classes. The spectral reflectance curves of classified classes generated from the ISODATA are illustrated in Fig. 2. From the spectrum of the original five classes and the comparison of raw imagery and the aerial photo, these classes were compressed into three distinct classes: water, dense vegetations, and grasslands and shrubs. Dense vegetations in the study area are predominantly herbaceous materials associated with high soil moisture that consequently has higher values in the NDWI (band 8) and the wetness index (band 12). Grasslands and shrubs occupy portions of the image that are more typically open and dry landscapes where the soil moisture content is lower. Their presence is indicated by higher brightness value (band 10) and lower values in the NDWI (band 8) and the wetness index (band 12).

Based on field observations, we consider that the primary larval habitats of *Cx. tarsalis* are where riparian vegetation is immediately adjacent to small water bodies. In our classification system riparian vegetation falls under the general classification of "dense vegetation," and habitat is identified in locating small water bodies and performing a proximal analysis to dense vegetation that represents emergent and riparian communities. Grasslands and shrubs are not considered as indicators or suitable larval habitats. A high pass 30-m filter was created to identify dense vegetation class immediately adjacent to water class, and these pixels were identified as *Cx. tarsalis* larval habitats.

Refinement of Classified Image for Habitat Suitability by Using Spatial Analysis. A scale issue was identified in the classification and field identification process: some very small ponds, usually smaller than 2 to 3 pixels, were improperly not classified as open water because they are mixed pixels in Landsat TM images. A significant number of these mixed pixels were classified as dense vegetations and are more properly classified as potential *Cx. tarsalis* larval habitats. Indeed, small standing water bodies have a greater potential for larval development than large open bodies of water, so identifying and classifying small bodies with adjacent dense vegetation is important but challenging given the limitation of pixel resolution. To refine these "missing" habitats, a secondary classification was performed by setting a threshold of exceedance in the panchromatic band, which has a higher spatial resolution (15 m). A rule set was established to filter out all dense vegetation pixels with a patch size smaller than 5 pixels (multispectral bands) because these small patches have the potential to be mixed water/riparian pixels in the 30-m data. These candidate pixels were further screened by eliminating the area where the digitial number (DN) value in the panchromatic was above a threshold set individually for each image (DN = 43 for 2001). Small patches with panchromatic DN less than the threshold are therefore classified as suitable habitat.

This refinement was performed for the 2001 image only. The 2004 image is Landsat 5 (Landsat 7 data are unavailable because of satellite equipment malfunction), which does not have a panchromatic band. These satellites are suitable for comparative analysis because they have exactly the same spectral range in bands 1–6. Although the habitat class in 2001 image accounts for ≈15.7% of all suitable habitats, there does not seem to be a temporal trend in the type and size of CBM discharge ponds in the study area. By losing access to the panchromatic band and not identifying habitat classes, we are underpredicting potential *Cx. tarsalis* habitat but not biasing the results with differential methods for the imagery. Future research will focus on higher spatial and spectral resolution data sets

Table 1. Error matrix of classification of *Cx. tarsalis* larval habitat

Classified image	Color infrared photo					Total	CA %
	>4 acres	>3 acres	>2 acres	>1 acre	>0.22 acre		
Habitat	14	18	49	99	185	211	87.68
Nonhabitat	2	6	19	62	257		
Total	16	24	68	161	442		
PA %	87.5	75.0	72.06	61.49	41.86		

CA, consumer's accuracy; PA, producer's accuracy. An area of 0.22 acre is equal to 1 pixel size in Landat TM images (30 by 30 m) (1 acre = 4,046.86 m^2).

Table 2. Classes resulting from unsupervised/supervised classification of the Powder River Basin

Feature	1999 ha	2004 ha	% increase
Water	478.8	836.9	74.8
Habitats	619.0	1084.5	75.2

1 ha = 10,000 m^2.

to isolate and identify small patches of potential larval habitat.

The final product generated from the classification procedure is shown as Fig. 4. By comparing the classified results with digitized small ponds in DOQQs, an error matrix was calculated and is presented as Table 1. Ponds are divided into different categories by their sizes because pond size is a primary limiting factor in the classification. Ponds smaller than the size of 1 pixel were not considered in this study, and we think that attempting to identify these ponds is beyond the capability of the Landsat TM images. The producer's accuracy reflects how well a pond on the ground (reality) is properly identified, and it is satisfactory for ponds larger than 0.8 ha (2 acres) (>70%). The producer's accuracy drops down to 61.5% after the pond size is smaller than 0.4 ha (1 acre). Overall, the consumer's accuracy, defined as how correct classified pond feature are, is ≈88%, indicating that the risk of overestimating habitat, primarily by inappropriately identifying vegetation not associated with small water bodies, is acceptable from a management perspective.

There was a 75.2% increase on the areas of potential larval habitats of *Cx. tarsalis* from 1999 to 2004 (Table 2; Fig. 5). This increase corresponds strongly to a commensurate 74.8% increase in area covered by water. Total area that falls into habitat increased from ≈619 to ≈1,100 ha. This correlation indicates the relative efficiency in the establishment of mosquito habitat with the increase in surface water. Given that CBM development is the primary source of new standing water bodies in this region, the observed increase in aquatic habitat with the potential to support larval mosquito populations is directly linked to growth in the CBM production.

Discussion

This study provides a method to rapidly assess potential larval habitats of *Cx. tarsalis* at a large spatial scale in a cost-effective way. The spatial proximity and size of water and dense vegetations are critical to separate larval habitats of *Cx. tarsalis* from other water and vegetation features. The classification procedure presented here successfully models potential larval habitats for water bodies larger than 0.8 ha (2 acres). The advantage of explicitly defining the spectral range and spatial relationship among habitat elements is that the ecological niche of larval habitat can be more precisely separated from other features. Results from the accuracy assessment indicate that the classification accuracy depends on the relative percentages of different sizes of water bodies. However, due to the spatial resolution of Landsat TM images (2–3 pixels), the classification will underestimate possible larval habitats in regions where the majority of water bodies are less than 0.8 ha (2 acres). The spectral signatures of these small areas are not separable from the signatures of other features such as streams and shadows of hillsides.

The average annual increase in CBM production from the Powder River Basin has been 66% since the mid-1990s, with a more rapid rate of growth after 2000 (Wyoming Outdoor Council and Powder River Basin Resource Council 2004). CBM development over the study period was extracted from online data published by WOGCC (2005). Wells have produced water were 1,784 in 1999, 8,941 in 2001 and 16,572 in 2004. The link between individual well production and location or concentration of surface discharge is lacking; wells are generally linked via a manifold and pond or surface discharges are not dependent on the location or number of wells. As such, the number of productive wells is a proxy for growth and potential releases of water. This relationship underscores the need for active assessment, because the spatial distribution of ponds and water releases is not predictive of the potential for larval habitat growth and cannot be used as a management tool.

According to the U.S. Geological Survey (2004), the Powder River Basin accounts for 30% in 2002 and 70% in 2003 of all human cases of the West Nile virus in Wyoming. Data from image classification presented here documented the dramatic increase of water discharge pools that are potential larval development sites for *Cx. tarsalis.* The methodology used in these analyses and results from changing land cover analyses can assist local authorities in the prioritization of sites for West Nile virus prevention programs. In addition,

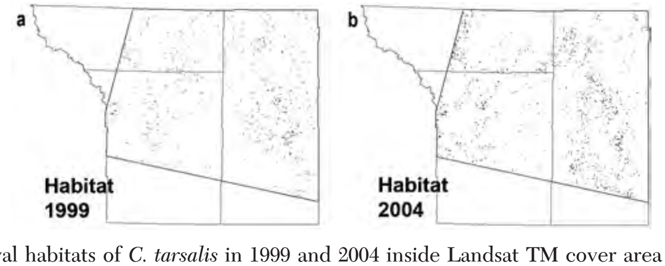

Fig. 5. Classified larval habitats of *C. tarsalis* in 1999 and 2004 inside Landsat TM cover area (Sheridan, Johnson, and Campbell counties).

the modeled larval habitats can be integrated into a global positioning system-guided control operation.

Although the risk of West Nile virus is determined by many factors, such as temperature and avian host availability, *Cx. tarsalis* habitats as a source of contribution continues to increase because of the thriving CBM development in this region. *Cx. tarsalis* larval habitat is associated with ponds that are water sources for many wildlife species and domestic animals such as cattle. These animals are in very close contact with infected *Cx. tarsalis.* Naugle et al. (2004) showed the decline of greater sage-grouse in this region in recent years with correlations to increased CBM activities.

The classification procedure developed in this study can be used to efficiently create a spatially explicit distribution of *Cx. tarsalis* larval habitats at the large scale. Although ponds smaller than one acre will be overlooked in this assessment, the product is valuable for the regional prediction of the vector population. Estimates of larval habitat are a conservative estimate but reflect the underlying spatial variability and density of risk. Given that permanent water stands are usually larger than 0.8 ha (2 acres), results from this study are suitable for long-term monitoring purposes. We are currently pursuing the use of higher spatial resolution images, to improve the resolution of spatial assessment and to better quantify the impact of CBM discharge water on mosquito larval habitat for ponds smaller than the detectable limit with Landsat.

Because *Culex* spp. mosquitoes are primary vectors of West Nile virus, the methods and activities in this study may provide a tool to identify *Culex* species habitats in other regions of North America. The image classification can be easily repeated and adopted. With the wide availability of Landsat TM data, this classification procedure can be applied more broadly in the future.

Acknowledgments

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Exhibit 30.13

This exhibit was not previously submitted in November 2023

Annual Bird Mortality in the Bitumen Tailings Ponds in Northeastern Alberta, Canada

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ANNUAL BIRD MORTALITY IN THE BITUMEN TAILINGS PONDS IN NORTHEASTERN ALBERTA, CANADA

KEVIN P. TIMONEY[1,3] AND ROBERT A. RONCONI[2]

ABSTRACT.—Open pit bitumen extraction is capable of causing mass mortality events of resident and migratory birds. We investigated annual avian mortality in the tailings ponds of the Athabasca tar sands region, in northeastern Alberta, Canada. We analyzed three types of data: government-industry reported mortalities; empirical studies of bird deaths at tailings ponds; and rates of landing, oiling, and mortality to quantify annual bird mortality due to exposure to tailings ponds. *Ad hoc* self-reported data from industry indicate an annual mortality due to tailings pond exposure in northeastern Alberta of 65 birds. The self-reported data were internally inconsistent and appeared to underestimate actual mortality. Scientific data indicate an annual mortality in the range of 458 to 5,029 birds, which represents an unknown fraction of true mortality. Government-overseen monitoring within a statistically valid design, standardized across all facilities, is needed. Systematic monitoring and accurate, timely reporting would provide data useful to all concerned with bird conservation and management in the tar sands region. *Received 17 November 2009. Accepted 5 May 2010.*

Global demand for unconventional energy sources such as coal bed methane, heavy oil, and bitumen has grown in recent years. Bitumen in northern Alberta, Canada, is extracted by two methods, *in situ* well-based approaches and truck and shovel open pit mining. The latter method produces ''tails'' during separation of bitumen from the sand. The tails, a mixture of process-affected water, residual hydrocarbons, brine, silts and clays, and metals are discharged into tailings ponds. The extent of tailings ponds in northeastern Alberta grew by 422% between 1992 and 2008 (Timoney and Lee 2009). The Athabasca tar sands development is one of the largest energy projects in the world. Production of bitumen is predicted to rise from the current 1.3 million barrels/day to three million barrels/day by 2018 (Alberta Energy 2009).

Water bodies along migration routes attract many bird species as they afford foraging, roosting, nesting, and resting opportunities (Ronconi 2006). A variety of deterrents have been used to discourage waterbirds from landing in tailings ponds such as floating and beach effigies, propane scare cannons, and sound-producing systems (Boag and Lewin 1980, Golder Associates Ltd. 2000, Ronconi and St. Clair 2006). Some birds that land at tailings ponds become oiled and a proportion of the oiled birds later die. Bird mortality rates from oiling have not been precisely measured, but casualties appear to be high for gregarious species, particularly for diving birds (Clark 1984). Bird migration is affected by weather as birds are more likely to land when they encounter headwinds, low temperatures, and precipitation (Newton 2007). Storms may increase the likelihood of bird oiling at tailings ponds (Ronconi 2006), and inclement weather may increase the probability of mass mortality events.

Oiled ducks may suffer from reduced insulation, increased metabolic rate, and hypothermia even from small amounts of oil (Hartung 1967, McEwan and Koelink 1973). Survival rates of rehabilitated birds may be as low as 1 to 20% for some species (Mead 1997). Birds from 43 species have died due to exposure to tailings ponds in the area, mostly waterbirds such as dabblers and divers: Mallard (*Anas platyrhynchos*), Common Goldeneye (*Bucephala clangula*), Northern Shoveler (*Anas clypeata*), Lesser Scaup (*Aythya affinis*), American Coot (*Fulica americana*), grebes, mergansers, geese, and shorebirds including Semipalmated Sandpiper (*Calidris pusilla*), Pectoral Sandpiper (*C. melanotos*), Stilt Sandpiper (*C. himantopus*), and Lesser and Greater Yellowlegs (*Tringa flavipes, T. melanoleuca*) (Sharp et al. 1975, Dyke et al. 1976, Gulley 1980, Ronconi 2006). Deaths of birds of prey, gulls, passerines, and other groups have also been documented. Mortality rates may be high even at small ponds: 27 dead birds were found at a 0.4-ha tailings pond lacking deterrents (Dyke et al. 1976). There may be continual ''incidental take'' of birds during the open water season, especially at night when human observations are impractical. Oiled birds in tailings ponds have been observed to sink out of

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sight (Dyke et al. 1976), minimizing the chance of detection.

Our objective was to provide estimates of annual bird mortality resulting from bitumen tailings pond exposure in northeastern Alberta, Canada through synthesis and analysis of available data. These data included numbers reported by industry to government and scientific data on mortality and landing rates at tailings ponds.

METHODS

Study Area.—We studied avian mortality in the Athabasca bitumen (tar) sands region (geographic center at 57° 03′ N, 111° 31′ W, Fig. 1) in the lower Athabasca River watershed north of the city of Fort McMurray, Alberta, Canada. The 120.6 km^2 of tailings ponds within the area of open pit mining, as of March 2008, covered 1.4 times the area of natural water bodies (84.9 km^2) composed of the surface of the Athabasca River (50.4 km^2) and lakes, ponds, and other river surfaces (34.5 km^2) (Timoney and Lee 2009; KPT and RAR, unpubl. data). The area lies within a convergence zone of North American waterfowl flyways; millions of birds migrate through northeastern Alberta *en route* to and from local and distant breeding areas in northern Alberta, the Peace-Athabasca Delta, Mackenzie River Valley, and the arctic (Butterworth et al. 2002, Thomas 2002, USDI 2009b). Thirty-five species and species groups of waterbirds, and 29 other species have been observed on one lease (Syncrude # 17) at the natural water body Mildred Lake (Sharp et al. 1975). More than 16,000 birds were observed flying over one tailings pond during spring migration (Ronconi and St. Clair 2006) while more than 25,000 swans, geese, ducks, Sandhill Cranes (*Grus canadensis*), and gulls were observed in daylight during a fall migration at Syncrude Lease # 17 (McLaren and McLaren 1985). The total number of migratory birds passing through the lower Athabasca River Valley is unknown.

Data Collection and Analyses.—Spot censuses and shoreline searches for dead birds of varying duration, extent, and frequency at tailings ponds of known areal extent during the open-water season (Gulley 1980, Van Meer and Arner 1985) were used to calculate bird mortalities per km^2 from which mortalities were adjusted to the 2008 areal extent of tailings ponds. Mortality data were collated from three companies with tailings ponds (Suncor 1990–2008, Syncrude 2000–2007, and Shell Albian 2000–2008). Data were obtained from reports produced by the companies (Syncrude 2008), and from the Alberta government (Sustainable Resources Development) under a freedom of information request (K. P. Timoney, October 2008). These data, reported by company, year, and mortality type were analyzed to obtain mean annual mortality. We estimated the total number of birds landing and subjected to oiling during spring migration at the Albian Sands Muskeg River Mine: landings/hr (from Ronconi and St. Clair 2006) and oiled birds/day (from Ronconi 2006).

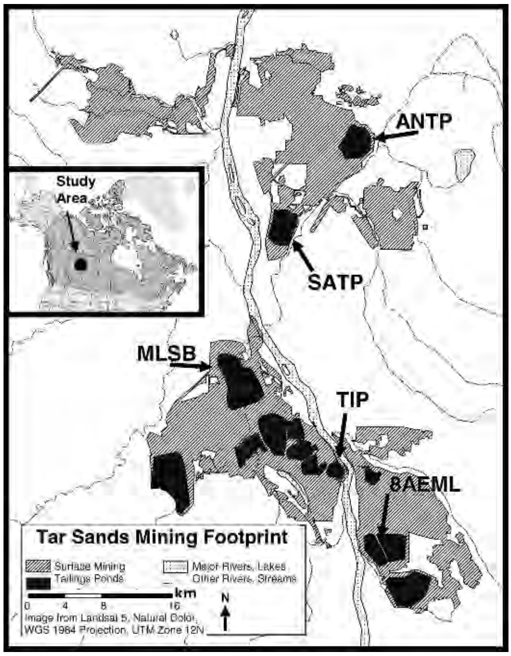

FIG. 1. Study area (modified from Timoney and Lee 2009). Areas (as of 19 March 2008) undergoing bitumen extraction are hachured; tailings ponds are black. Tailings pond names are MLSB = Mildred Lake Settling Basin; ANTP = Aurora North tailings pond; SATP = Shell Albian tailings pond; TIP = Tar Island Ponds 1 and 1A; 8AEML = Suncor Millennium tailings ponds 8A and EML.

RESULTS

Mortality Rates Estimated by Systematic Surveys.—Systematic surveys for dead birds at tailings ponds (Table 1), used to calculate mortality per km^2 (range 7.2 to 145.2 birds), were extrapolated to estimate total potential mortality based on 120.6 km^2 of tailings ponds in 2008. An estimate based on the lowest observed mortality at

TABLE 1. Estimated annual bird mortality/km²/year in the Athabasca tar sands tailings ponds based on spot counts and systematic shoreline surveys.

Site	Area (km²)[a]	Year	Dead birds	Dead birds/km²	Reference[c]	Comments
MLSB	12.25	1984	94	7.68	1, 3	scare cannons, human effigies
MLSB	11.74	1985	84	7.15	1, 3	scare cannons, human effigies
MLSB	11.58	1980–1983[b]	189.5	16.36	1, 3	scare cannons, human effigies
Pond 1	1.86	1977	77	41.40	2	human effigies; fresh tailings received 95% of days (Apr–Oct)
Pond 1	1.86	1978	79	42.47	2	human effigies; fresh tailings received 100% of days (Apr–Oct)
Pond 1	1.86	1979	270	145.16	2	human effigies with artificial lighting at night; fresh tailings received 92% of days (Apr–Oct)
Pond 1A	0.56	1977	43	76.79	2	deterrents?[d]; fresh tailings received 34% of days (Apr–Oct)
Pond 1A	0.56	1978	31	55.36	2	deterrents?[d]; fresh tailings received 25% of days (Apr–Oct)
Pond 1A	0.56	1979	33	58.93	2	deterrents?[d]; fresh tailings received 0% of days (Apr–Oct)

[a] Areas of MLSB derived from planimetry of airphotographs (1980, AS2165-13; 1984, AS3051-5; 1986, AS3356-280; Ponds 1 and 1A areas derived from Gulley (1980).
[b] Dead birds/year 1980–1983 derived mathematically from reported values for 1984 and 1980–1984 (Van Meer and Arner 1985): 1980–1984 average mortality of 170.4 birds/year; total birds dying 1980–1984 = 170.4 × 5 = 852 birds; 1984 mortality of 94 birds; 1980–1983 average mortality = (852 − 94)/4 = 189.5 birds/year, or 16.36 birds/km²; the average weighted mean mortality 1980–1985 = ((16.36 × 4) + 7.68 + 7.15)/6 = 13.38 birds/km². The high estimate of annual mortality is the weighted mean mortality per km²; it is the sum of 500.38 birds/km² for 12 years of data (1980–1983 comprises 4 years of data), 500.38/12 = 41.70 birds/km².
[c] References: 1 = Van Meer and Arner (1985); 2 = Gulley (1980); 3 = Golder Associates Ltd. (2000).
[d] Queries sent to Suncor (17 Nov to 12 Dec 2008) regarding deterrents in use on Pond 1A during 1977–1979; no reply received to date (4 May 2010).

Syncrude's Mildred Lake Settling Basin (MLSB) of 7.2 birds/km² in 1985 yielded an annual mortality of 863 birds. A medium estimate based on Syncrude's MLSB (1980–1985) average mortality of 13.38 birds/km² yielded an annual mortality of 1,614 birds. A high estimate based on the weighted mean mortality rate for all years at Syncrude's MLSB and Suncor's Tar Island Ponds 1 and 1A of 41.7 birds/km² yielded an annual mortality of 5,029 birds.

Industry-based Annual Mortality Reported to Government.—Annual mortality attributed to oiling over the period 2000 to 2007 ranged from 17 to 201 birds. The weighted mean (± SD) annual mortality was 65 ± 59 birds. (Table 2). Additional annual mortalities attributed to 'other' and to 'unknown' causes (details in Table 2) averaged (± SD) 13 ± 9 (max 31 in 2007) and 16 ± 9 birds, respectively. Industry data had poor agreement with the government data released under the freedom of information request (Table 3); the mean difference was 19%.

Annual Bird Mortality Estimated by Landing and Oiling Rates.—A spring landing rate of 121.44 birds/day in a 3.5 km² tailings pond was calculated, resulting in an estimated rate of 34.69 landings/km²/day during daylight hours only (low estimate, Table 4). We calculated 54.93 landings/day (109.86 landings/km²/day) (high estimate, Table 4) from observations at a 0.50-km² area where deterrent testing occurred (RAR, unpubl. data not previously reported in Ronconi and St. Clair 2006). Scaling for the total area of tailings ponds in 2008, about 125,513 to 397,408 birds may land during a 30-day spring migration period. Thirteen oiled waterbirds and shorebirds were found during the same period and at the same site (Ronconi 2006), most of which were covered in >50% oil, from which oilings/day and the proportion of landed birds becoming oiled were calculated (Table 4). We estimate that 286 to 905 birds may be oiled during spring migration at an overall oiling rate of 0.2278% for birds that landed on ponds. About 229 to 815 birds may die each spring due to oiling if an oiled bird is unable to land more than once, and 80 to 90% of oiled birds die (Discussion).

DISCUSSION

Uncertainties in Mortality Estimates.—Bird oilings may peak in August and September rather than in spring (Van Meer and Arner 1985), and it is reasonable to double the spring mortality to derive an annual mortality of ~458 to 1,630 birds.

TABLE 2. Bird mortalities attributed to oiling, 'other' and 'unknown' causes released by the Alberta Government for petroleum companies with tailings ponds in northeastern Alberta.[a]

Year	Oiling[b]			Other			Unknown		
	Suncor	Syncrude	Albian[b]	Suncor	Syncrude	Albian	Suncor	Syncrude	Albian
1990	103			0			0		
1991	93			0			0		
1992	194			0			2		
1993	135			0			4		
1994	87			0			1		
1995	43			0			0		
1996	72			0			4		
1997	71			0			6		
1998	80			0			3		
1999	48			0			10		
2000	193	8		0	2	1	12	7	0
2001	2	15		0	2	0	23	3	0
2002	17	20		1	6	3	1	2	1
2003	15	16	17	2	23	3	2	5	0
2004	10	33	2	0	5	2	2	9	1
2005	3	8	14	2	18	2	1	16	1
2006	3	57	3	4	8	7	3	8	4
2007	9	10	26	1	7	6	6	19	6
2008[c]	16		4	0	2	1	0	2	4
Recent Mean ± SD[b]	31.5 ± 65.5	20.9 ± 16.7	12.4 ± 10.0	1.2 ± 1.4	8.9 ± 7.6	3.0 ± 2.4	6.2 ± 7.7	8.6 ± 6.0	1.6 ± 2.2

[a] 'Other' includes electrocution, collisions, predation, fights with other birds, and natural causes; 'Unknown' includes incidents where company was not able to identify cause of death and incidents where cause of death was not reported.
[b] Tailings pond at Shell Albian began to fill in 2003; mortality due to oiling not expected prior to 2003. Calculations of recent tailings pond mortalities used years 2000–2007 for Suncor and Syncrude and years 2003–2007 for Shell Albian. Mortality means for 'other' and 'unknown' use the period 2000–2007. Mortality means are for each company and mortality type. Average mortalities by year, 2000–2007, oiling 64.8 ± 58.7, other 13.1 ± 9.3, and unknown 16.5 ± 9.1.
[c] Values for 2008 were 'year to date' current to July 2008 with the exception of Syncrude for which the death of 1,606 ducks at the Aurora North tailings pond in April 2008 was not made public until 2009.

This adjustment to the mortality estimate may be conservative as it does not include mortalities that occur before spring, between spring and fall migration, and after fall migration. Annual tailings pond mortality estimates derived from mortality surveys (863 to 5,029 birds) and landing-oiling rates (458 to 1,630 birds) are roughly of the same magnitude. Self-reported oiling mortality data from industry provide the lowest estimate (65 bird deaths/year) whereas Wells et al. (2008) provide a high estimate of 8,676 to 156,168 bird deaths/year. Wells et al. (2008) assumed that all birds that land at tailings ponds are oiled and that peak landing rates exist 24 hrs/day for 100 days. Our mortality estimates may be conservative given that 500,000 to one million birds die annually at oilfield wastewater ponds in the United States (USDI 2009a). Those wastewater ponds are similar to bitumen tailings ponds in their mixture of water, residual oil or bitumen, and salts.

The presence of extensive tailings ponds

TABLE 3. Annual bird mortality at Syncrude[a] as reported by the Alberta government and by Syncrude (2008).

Source	Year							
	2000	2001	2002	2003	2004	2005	2006	2007
Alberta Government	17	20	28	44	47	42	73	36
Syncrude	20	21	31	44	69	55	46	35
Difference[b], %	−18	−5	−11	0	−47	−31	37	3

[a] Combined Mildred Lake and Aurora leases.
[b] Difference = (Government − Syncrude/Government) × 100; mean difference without regard to sign = 19%.

TABLE 4. Rates of landing and the proportion of birds that subsequently become oiled at Shell Albian Sands tailings pond during April–May 2003.[a]

	Number of birds landing	Landings/hr	Landings/day[c]	Oiled birds	Oilings/day	% Landed birds that became oiled
Ducks	536	3.99	63.69	7	0.149	0.23
Shorebirds	444	3.30	52.76	4	0.085	0.16
Geese/Swans	10	0.07	1.19	1	0.021	1.79
Gulls	13	0.10	1.54	1	0.021	1.38
Other waterbirds [b]	19	0.14	2.26	0	0.000	0.00
Overall	1,022	7.60	121.44	13	0.277	0.23

[a] Data compiled from spring migration studies in the 3.5 km^2 main tailings pond at Shell Albian Sands, Muskeg River Mine (Ronconi 2006, Ronconi and St. Clair 2006) yielding a low estimate of 34.69 landings/km^2/day; there were 54.93 landings/day within the 0.50 km^2 observation area yielding a high estimate of 109.86 landings/km^2/day; 47 days of observation for oiled birds.

[b] Loons, grebes, cranes, herons, cormorants, and coots.

[c] Observations for daylight hours only; average 15.97 hrs of daylight between 18 April and 29 May, 134.4 hrs of observation (source: www.almanac.com/rise for Fort McMurray, AB, Canada).

containing bitumen, polycyclic aromatic hydrocarbons (PAHs), naphthenic acids, brine, heavy metals, and ammonia along an internationally significant migratory bird corridor poses long-term threats to migratory and resident birds (Schick and Ambrock 1974, Wells et al. 2008). Tailings ponds may pose the greatest threat in spring when warm effluent-fed tailings ponds provide open water at a time when natural water bodies remain frozen; however, a high risk of oiling may extend throughout the open water season (Van Meer and Arner 1985).

There are four aspects of our estimates that influence their accuracy. First, no nocturnal observations of migrating or landing birds were made. Many birds migrate at night (Richardson 1971, Blokpoel 1973, Blokpoel and Burton 1973), but landing rates during darkness are unknown. Many birds migrate at night and mortality rates might be higher if data from night-time observations were available. There are also no observations for November through early April, when natural water bodies are frozen but large areas of tailings ponds remain unfrozen due to addition of warm tailings. The frequency of landings then is unknown, but is presumably greater than zero for resident birds. Higher rates of nocturnal landings and landings in non-migratory periods would increase our estimates.

A second source of estimation error is that numbers of birds flying over, landing, becoming oiled, or being found dead are an unknown fraction of the true parameter values. Some of these parameters were estimated from the most recent and systematically collected data available (e.g., Ronconi 2006, Ronconi and St. Clair 2006); however, without data from other sites and years, there is no means to assess variation in rates of birds landing, becoming oiled, or dying.

Third, we assumed a mortality rate of 80 to 90% for birds that came in contact with oil. Mortality rates of oiled birds are unknown (Clark 1984), but even very small amounts of oil may kill birds (Hartung 1967, McEwan and Koelink 1973) and survival rates of rehabilitated oiled birds may be as low as 1 to 20% (Mead 1997). Our estimates assume a small proportion (10–20%) of oiled birds may survive oiling.

Finally, by scaling our estimates from individual tailings ponds to the areal extent of tailings ponds in the region, we assumed that bird use and associated mortalities are similar across sites. This assumption remains untested and, for some species such as shorebirds, the extent of shoreline contaminated with bitumen may be a better predictor of mortality than extent of open water.

Individual events may result in large variations in mortality. A migratory waterfowl mortality event at the Syncrude Aurora North tailings pond occurred in April 2008 at which 1,606 dead waterfowl were later found (CBC 2008, 2010). Provided that all dead waterfowl were found and no non-waterfowl died, the single event resulted in a mortality of 162 birds/km^2 well in excess of our highest estimate (Table 1). The frequency of mass mortality events is unknown.

Inconsistencies and Deficiencies in Reporting Bird Mortality.—We note three major shortcomings in the data provided by government and industry. First, mortality estimates based on mortality surveys and landing/oiling rates are far higher than those reported by government. Second, industry-reported mortalities often do not match mortalities reported by the government

(Table 3), even though government and industry numbers should be identical. Third, the bird mortality data released by government lack detail. Only company name and total bird mortality for each year and general cause of death are reported; this results in loss of valuable data on location, date, and circumstances of specific incidents.

Sampling design, including appropriate sample size, sampling effort, and accurate detection and identification of species is a critical aspect of an effective monitoring protocol (McComb et al. 2010). Numbers of bird mortalities are directly related to search effort and sampling design. Industry-reported data on bird deaths are problematic as they are not systematic, repeatable, and statistically robust. Review of mortality data in Syncrude annual reports indicates that few of the observations come from tailings ponds, which is likely where most oiled birds die. Syncrude (2006, 2008) reported underestimating mortality when explaining an increasing trend in bird mortality in recent years as partially attributable to improved monitoring and reporting practices.

The Need for Improved Data.—Currently, neither the total number of birds migrating through the region nor the total annual bird mortality attributable to tailings ponds are known with sufficient scientific rigor. Data on mortalities during extreme weather events are lacking. The fate of lightly-oiled birds that continue migration, in particular to summer breeding areas, is unknown. Important questions remain about the variability in landing and oiling probability with season, weather conditions, time of day, and pond size and location. Questions also remain about mortality detection efficiency in relation to sampling effort, monitoring protocols, and tailings pond size. The *ad hoc* monitoring by industry, sanctioned by government, is inconsistent, cannot answer these questions, and undoubtedly underestimates actual mortality.

CONSERVATION IMPLICATIONS

The pace and scale of development of the Athabasca tar sands is unprecedented in North American history. The industrial footprint and resultant habitat loss may double in 15 years and will certainly increase bird mortality rates. Open pit bitumen extraction may exert population-level impacts upon migratory and resident birds, and is capable of causing mass mortality events. Existing natural water bodies should be protected to help offset landings of birds in tailings ponds (Ronconi 2006). Production of liquid tailings should be phased-out before this expansion of the industry occurs.

Tailings ponds exceed the extent of natural water bodies in the area, continue to increase in extent, and lie along an internationally significant flyway; thus, they may pose a significant regional mortality risk. Harmful effects of tailings ponds are not limited to oiling of waterbirds. Ingestion of bitumen grit by waterfowl may be a significant route of exposure to contaminants (King and Bendell-Young 2000). Nesting Tree Swallows (*Tachycineta bicolor*) exposed to process-affected wetlands have higher mortality, hormonal stress, nestling parasitism, and reduced nesting success (Wayland and Smits 2004, Gentes 2006). The effects were attributed to PAH exposure, possibly through feeding on contaminated insects.

A variety of strategies have been tested to reduce the attraction of birds to industrial developments (Brough and Bridgman 1980, Stevens and Clark 1997, Read 1999; and reviews by Bomford and O'Brien 1990, Donato et al. 2007). The tar sands industry in northeastern Alberta has been using landing deterrents such as propane cannons and scarecrows for >30 years (Boag and Lewin 1980, Gulley 1980, Golder Associates Ltd. 2000). One of the long-standing problems of bird deterrents is habituation (Bomford and O'Brien 1990, Stickley et al. 1995, Conover 2001). A recent comparison of modern deterrent techniques found the odds of landing at ''protected'' bitumen tailings ponds remained high relative to non-deterrent controls (Ronconi and St. Clair 2006). Overall, these authors observed no significant difference in the deterrence value of industry standard versus radar-activated systems. The effectiveness of existing deterrents may be enhanced with development of compensation ponds (Read 1999, Donato et al. 2007), providing clean water and a positive stimulus for birds deterred from tailings ponds.

Government should assume responsibility for development of systematic monitoring and research on tailings pond bird landing, oiling, and mortality rates. The work should be conducted by independent scientists using a statistically valid sampling design with emphasis on spring and fall migration. A rigorous and systematic monitoring plan standardized across all facilities is likely to yield a better understanding of the factors contributing to avian mortality at tailings ponds than *ad hoc* monitoring. These data would be valuable to development and refinement of effective mitigation strategies (e.g., deterrents and compensation ponds) as a component of an adaptive management approach towards reducing avian mortalities. Well-designed monitoring programs help managers and policy makers to reach informed decisions based on facts (McComb et al. 2010). Systematic monitoring and accurate, timely reporting would provide data useful to all concerned with bird conservation and management in the tar sands region.

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Exhibit 30.14

This exhibit was not previously submitted in November 2023

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NEWS

Oil companies charged in bird deaths

GRAND FORKS - Seven oil companies operating in western North Dakota face federal charges of killing migratory birds that allegedly died when they landed in oil field pits and wastewater disposal facilities.

By DL News Staff
August 26, 2011 at 7:38 AM

Share

GRAND FORKS - Seven oil companies operating in western North Dakota face federal charges of killing migratory birds that allegedly died when they landed in oil field pits and wastewater disposal facilities.

The charges under the Migratory Bird Treaty Act cite the losses of 28 ducks and other birds in oil waste pits between May 6 and June 20. Federal laws require pits to be bird-proofed with fences, screens and nets.

The violations "should be troubling to those interested in preserving North Dakota's rich heritage of hunting and fishing and to the many oil companies who work hard to follow the laws protecting our wildlife," U.S. Attorney Timothy Purdon said in a statement.

A dozen of the dead birds were found in pits operated by Slawson Exploration Co. of Wichita, Kan., including three mallards, two gadwalls, two blue-winged teal, one redhead, one common golden eye, one northern pintail and two birds of unknown species.

Other companies charged are ConocoPhillips Co., of Houston; Newfield Production Co., of Houston; Brigham Oil and Gas LP, of Williston; Continental Resources Inc., of Enid, Okla.; Fidelity Exploration & Production Co., of Denver, and Petro Hunt LLC, of Dallas.

Ron Ness, president of the North Dakota Petroleum Council, an industry association, said that protecting wildlife "is something the oil companies take seriously."

"You've got a lot of pits out there," he said. "There are nearly 6,000 wells out there. They don't all have areas these birds can be attracted to, but there are hundreds and hundreds of such sites. We don't know how many birds are killed on roadways, how many are killed by power lines, and how many were lost because of flooding on the Missouri and Souris rivers.

"You net these pits and do all these things, but the reality of putting a net out in North Dakota, with the winds we have, and all sorts of things happen," he said.

The Associated Press reported that none of the companies responded to requests for comment.

The maximum sentence for violation of the Migratory Bird Treaty Act is six months in federal prison and a $15,000 fine, according to the U.S. attorney's office.

The seven companies charged are to make initial appearances in U.S. District Court in Bismarck on Sept. 22.

The charges come after a plea issued last week by the U.S. Fish and Wildlife Service for operators in North Dakota's oil fields to step up efforts to prevent depredation of migratory birds in skim pits, reserve pits and oil field wastewater disposal facilities.

The U.S. Attorney's Office said the cases cited in Thursday's release were investigated by the U.S. Fish and Wildlife Service.

With the onset of fall migration approaching, the service warned last week that as many as 1 million birds are killed annually in oil field production areas, including ducks, hawks, owls and songbirds, as well as bats, small mammals and big game.

Noting that many oil field operators use netting to keep birds and other wildlife from pits, the wildlife service said those nets require intensive maintenance. "Pits or ponds with nets sagging into the pit fluids are just as lethal to birds as oil pits with no netting," the service said in a statement released last week.

Studies have shown that other methods used by oil field operators to deter birds and other wildlife from pits, such as metal reflectors and flashing strobe lights, are not effective.

Prevention of small spills, the proper securing of hoses, valves and containers, and immediate cleanup of spilled oil "will go a long way to preventing wildlife mortality in oil and gas production facilities," the service stated.

In their "Running With Oil" series last year, the Herald and other newspapers of Forum Communications Co. identified the impact on migratory birds as one of the potentially damaging side effects of the oil boom.

Much wildlife habitat is being converted to oil drilling pads and roads, and the waste pits and spills pose deadly dangers to birds and other animals.

Ron Shupe, a retired wildlife biologist and head of the North Dakota chapter of the Wildlife Society's energy committee, said in the 2010 Forum Communications report that the industry had made great strides over the past 20 years "to develop technologies that are kinder to the environment," but that no state agency had the staff and resources to monitor long-term effects on wildlife of rapid oil field development.

Chuck Haga writes for the Grand Forks Herald.

Exhibit 30.15

This exhibit was not previously submitted in November 2023

ENERGY & INDUSTRY

Oil industry profits don’t pay for cleanup

A failure of regulation has allowed industry to avoid the true cost of cleaning up its unplugged wells.

Mark Olalde *and* ***Nick Bowlin*** ***February 26, 2024***

Pump jacks on a ridgeline in Wyoming.
Bureau of Land Management

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In the 165 years since the first American oil well struck black gold, the industry has punched millions of holes in the earth, seeking profits gushing from the ground. Now, those wells are running dry, and a generational bill is coming due.

Until wells are properly plugged, many leak oil and brine onto farmland and into waterways and emit toxic and explosive gasses, rendering redevelopment impossible. A noxious lake inundates **West Texas ranchland**, oil bubbles into a **downtown Los Angeles** apartment building and gas seeps into the yards of **suburban Ohio homes**.

But the impact is felt everywhere, as many belch methane, the second-largest contributor to climate change, into the atmosphere.

There are more than 2 million unplugged oil and gas wells that will need to be cleaned up, and the current production boom and windfall profits for industry giants have obscured the bill’s imminent arrival. **More than 90% of the country’s unplugged wells** either produce little oil and gas or are already dormant.

By law, companies are responsible for plugging and cleaning up wells. Oil drillers set aside funds called bonds, similar to the security deposit on a rental property, that are refunded once they decommission their wells or, if they walk away without doing that work, are taken by the government to cover the cost.

But an analysis by *ProPublica* and *Capital & Main* has found that the money set aside for this cleanup work in the 15 states accounting for nearly all the nation’s oil and gas production covers less than 2% of the projected cost. That shortfall puts taxpayers at risk of picking up the rest of the massive tab to avoid the environmental, economic and public health consequences of aging oil fields.

The estimated cost to plug and remediate those wells if cleanup is left to the government is $151.3 billion, according to the states’ own data. But the actual price tag will almost certainly be higher — **perhaps tens of billions of dollars more** — because some states don’t fully account for the cost of cleaning up pollution. In addition, regulators have yet to locate many wells whose owners have already walked away without plugging them, known as orphan wells, which states predict will number at least in the **hundreds of thousands**.

“The data presents an urgent call to action for state regulators and the Department of the Interior to swiftly and effectively update bond amounts,” said Shannon Anderson, who tracks the oil industry’s cleanup as organizing director of the Powder River Basin Resource Council, a nonprofit that advocates for Wyoming communities. Anderson and nine other experts, including petroleum engineers and financial analysts, reviewed *ProPublica* and *Capital & Main*’s findings, which were built using records from 30 state and federal agencies.

“We have allowed companies intentionally to do this.”

“We have allowed companies intentionally to do this,” said Megan Milliken Biven, who reviewed the data and is a former program analyst for the Bureau of Ocean Energy Management, a federal regulator of offshore oil rigs, and founder of True Transition, a nonprofit that advocates for oil field workers. “It is the inevitable consequence of an entire regulatory program that is more red carpet than red tape.”

It Could Cost $151.3 Billion to Clean Up the Country’s Major Oil Fields

These 15 states, which produce 99% of the country’s oil, have $2.7 billion available to plug wells if that work falls to them.

Sources: State oil regulators and the Department of the Interior, via public records requests by ProPublica and Capital & Main; Enverus.

Regulatory agencies in several states maintain that they have adequate tools to protect taxpayers, such as the authority to require companies to post larger bonds as their wells stop producing. Other states are **working to reform their bonding systems**. Industry representatives, meanwhile, say they have done their part by paying fees on oil production that help fund states’ well-plugging efforts.

“Our industry is taking action every day to address the permanent closure of historic oil and natural gas wells and the remediation of historic well sites in accordance with applicable federal and state laws,” Holly Hopkins, a vice president of the American Petroleum Institute, the industry’s major trade group, said in a statement.

A graveyard of rusting wells rising from once-picturesque sand dunes near Artesia, New Mexico, tells a more complicated story.

Around the corroding skeletons of pump jacks, the ground is stained black from spills. Leaking hydrogen sulfide, which reeks of rotten eggs, has turned the air toxic, making each breath burn. At the base of **one salt-caked well**, a sign indicates who is responsible for the mess. Barely legible beneath splattered oil, it reads "Remnant Oil Operating."

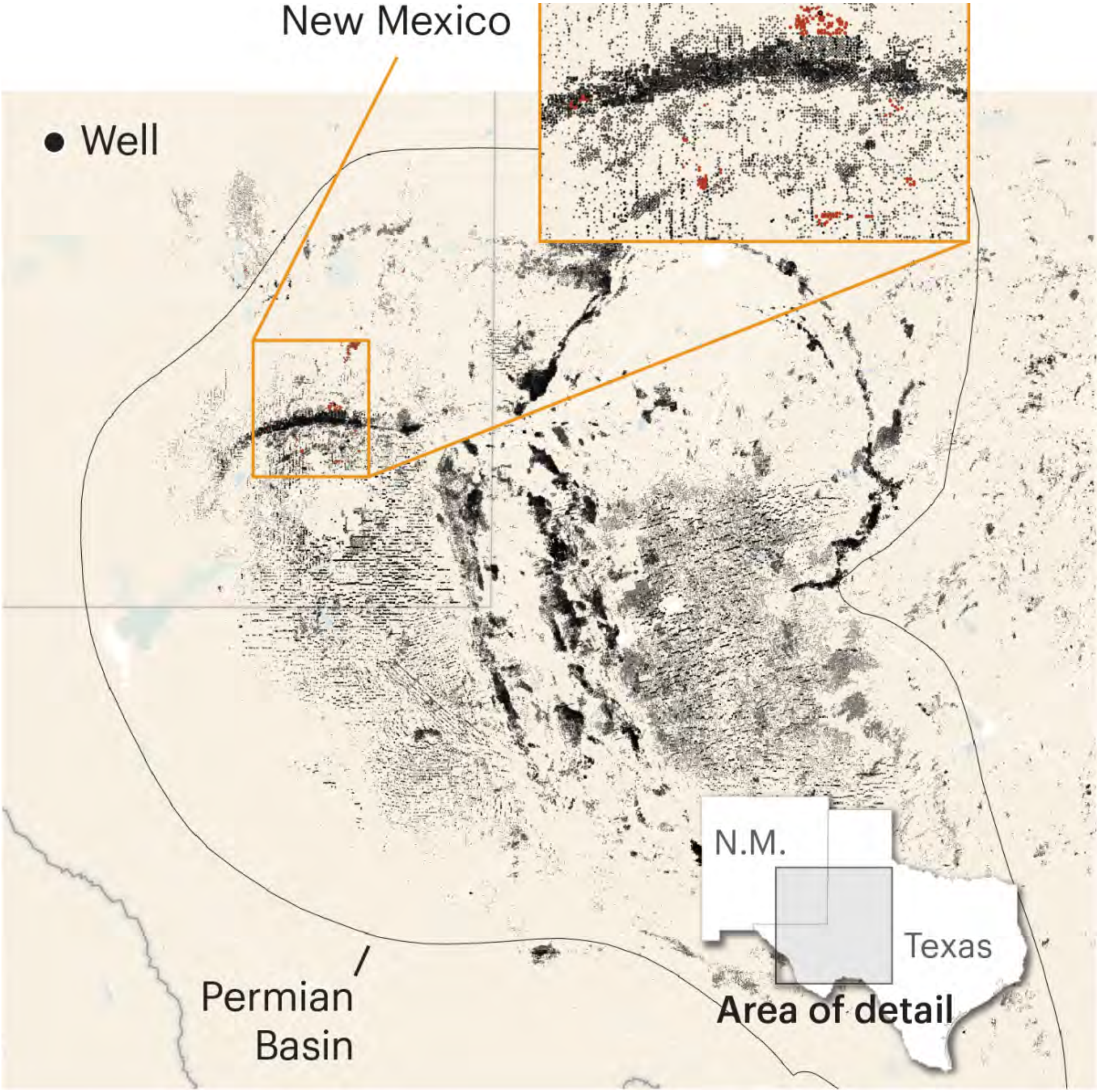
The story of Remnant is the story of the American oil industry.

The industry's household names — Chevron, ExxonMobil and others — often reap the biggest profits from any given oil field. As the booms fade and production falls, wells are sold to a string of ever-smaller companies, many of which let the infrastructure fall into disrepair while violations and leaks skyrocket. The number of idled wells soars too, as companies warehouse them to avoid costly cleanup. By this point, regulators' hands are tied because the bonds states demand to use as leverage are so small. Seeing little incentive to plug wells and get their tiny bonds back, companies slip into bankruptcy court, where executives are protected from their environmental liabilities. When the dust settles, the government is on the hook for the now-orphaned wells.

The practice is so tried-and-true that researchers and activists call it "the playbook."

As the company's name implies, Remnant gathered the industry's dregs into a portfolio of several hundred wells. Drilled decades ago by larger companies, their most productive days were behind them. When Remnant arrived in 2015, it briefly boosted production, but regulatory violations, bad bets and the oil fields' age caught up with the company. Within four years, Remnant filed for bankruptcy protection, and its leadership shuffled assets and liabilities between companies the executives managed.

What's left of Remnant is 401 wells scattered across the New Mexico countryside. While a few are still pumping, more are idle and potentially already orphaned, joining thousands of other wells that are sitting unplugged and in need of cleanup across the wider region. Regulators here in the Permian Basin, the world's most productive oil field, must contend with Remnant and other undercapitalized companies like it that could add even more wells to the list of orphans.



Remnant representatives did not respond to *ProPublica* and *Capital & Main*’s requests for comment.

Over their lifespans, the wells that remain in the hands of Remnant and a related company generated roughly $2 billion in revenue, when adjusted for inflation, enough to cover the cost of their cleanup many times over. This is according to estimates produced from state production data by *ProPublica*, *Capital & Main* and Texas-based petroleum reservoir engineer Dwayne Purvis.

The New Mexico State Land Office sent letters in 2023 demanding that cleanup begin. Remnant’s executives have yet to comply.

Seeking fortunes

As wildcatters scoured Texas for oil in the 1920s, one hopeful investor christened their well in honor of Saint Rita of Cascia — **the patron saint of impossible causes** — asking for a miracle. The gusher that followed ignited a drilling frenzy in the Permian Basin, from West Texas to southeastern New Mexico.

By the late 1940s, the Square Lake Pool had come alive among New Mexico’s sand dunes. Anadarko Production Company — now part of the $50 billion Oxy Petroleum — took over **the oil field in the 1960s** and increased production. To keep the oil and gas flowing, Anadarko turned to unconventional methods: fracturing underground rock, **injecting wells with gelled water and frac sand** and **waterflooding**. The **chemical treatments continued into the 1980s**, but production steadily declined as the wells aged and underground oil reservoirs were depleted.

In 1995, Xeric Oil & Gas Corp. acquired much of the field. Two years later, Xeric transferred the wells to GP II Energy Inc. In the two decades that followed, the wells ping-ponged to CBS Operating Corp., Boaz Energy LLC, Memorial Production Operating LLC, Marker Oil and **finally, in 2017, to Remnant**.

Remnant was the brainchild of Everett Willard Gray II, Robert Stitzel and Marquis Reed Gilmore Jr., oilmen out of Midland, Texas, the heart of the Permian. They set up shop north of downtown, their office surrounded by those of other oil companies, a politician and banks in a six-story office building rising above a parking lot full of white pickup trucks.

Initial investments in the wells succeeded in reversing the declining production and squeezed out tens of millions of dollars of additional revenue, estimates based on state data show.

But Gray, Stitzel and Gilmore — who did not respond to requests for comment — reduced the workforce that serviced the wells and limited repairs to cut costs. Regulators noted 146 infractions in the years Remnant and a related company operated the wells, according to New Mexico Oil Conservation Division data. Among them: leaks and spills, degraded wells, a lack of infrastructure to contain spills and “contaminated material on location.” The records show Remnant only brought two of the infractions into compliance, but it continued pumping.

Peer-reviewed studies have found that wells emit methane, a greenhouse gas that in the short term has 85 times the warming impact of carbon dioxide, at a higher rate as they move down the oil industry food chain, from majors to thinly capitalized operators like Remnant.

Transferring wells between companies has historically been approved automatically in New Mexico, as long as the company receiving the wells is in compliance with inactive-well rules and has a bond, according to Oil Conservation Division acting Director Dylan Fuge.

As oil fields age and are passed between companies, it's also common to let wells stand inactive temporarily to wait out a price dip or complete maintenance. But idling is often a prelude to a well being orphaned, and after a few months of inactivity, the chance **that a well never produces again rises significantly**.

Across the country, more wells are idle than producing, according to an analysis of data from energy software company Enverus.

Despite a New Mexico law that requires companies to plug, restart or get approval to temporarily idle wells that haven't produced for 15 months, *ProPublica* and *Capital & Main* identified more than 3,100 oil and gas wells in the state — 4% of the state's portfolio — that sit unproductive and out of compliance, a step away from being orphaned.

A bill introduced in this year's legislative session — written by the Oil Conservation Division, the industry and certain environmental groups — would've reformed New Mexico's Oil and Gas Act, giving the agency more authority to intervene to stop transfers that pose a risk of leaving wells orphaned. The bill died on the floor of the state's House of Representatives.

Any reforms would likely come too late for the oil fields in Remnant's hands, where numerous wells are already idle.

Hesitant to regulate

On a brisk November day, *ProPublica* and *Capital & Main* reporters examined a Remnant well that, like the company, was listed in state records as inactive. Oil coated the wellhead, rust crept across the pump jack and a faded sign bore Remnant's coat of arms — a bird of prey with outstretched wings perched on a shield.

Suddenly, the well creaked to life, producing for a dead company. A haze appeared. Methane, typically invisible to the naked eye, leaked in such a high concentration that the air shimmered. A handheld gas detector aimed at the wellhead screeched a warning — the amount of escaping methane had made the air explosive.

That day's production and emissions never appeared in state records.

Methane leaks from a Remnant well listed as inactive in state records. The gas is invisible to the naked eye but detectable as a black plume using specialized infrared camera technology. Credit: FLIR footage courtesy of Charlie Barrett/Earthworks

ProPublica and *Capital & Main* reporters visited dozens of Remnant wells and tank batteries — facilities used for oil storage and early stages of processing — scattered across this rural stretch of New Mexico. Multiple sites emitted explosive levels of methane, with one leak clocked at 10 times the concentration at which the gas can explode.

Several wells belched sour hydrogen sulfide at concentrations that maxed out the gas detector, registering levels three times as high as what is “immediately dangerous to life or health,” **according to the National Institute for Occupational Safety and Health**.

Oil Conservation Division inspectors hadn’t visited some of the wells since 2017, according to agency records.

Two hundred fifty miles northwest of these oil fields, New Mexico’s Democrat-controlled government in Santa Fe has for years made big promises on climate change and the environment. But there has been little action to regulate the industry in ways that could hit the bottom line of the state’s petroleum companies and oilmen like Remnant’s

Gray, Stitzel and Gilmore. The taxes and royalties the industry pays, which the state **has tied to public education funding**, typically account for **more than a quarter** of the state's general fund, earning it a nickname — "golden goose."

This close relationship to the industry cuts across parties. When Republicans were in power, the head of the New Mexico Environment Department left to run the New Mexico Oil and Gas Association. Now, the state's Democratic leaders **take major fossil fuel donations**, **publicly assert** that they will not target the industry with aggressive regulations, and block reform.

State Rep. Joanne Ferrary, a Las Cruces Democrat who has worked on oil legislation, had a simple explanation for what dooms these efforts: money. She pointed to the industry's spending on lobbying as well as the threat of losing taxes and royalties. "We do get a lot of money from them," she said, "but those are our resources and they're not doing us any favors."

Consider the state's Office of Natural Resources Trustee, which pursues polluters for financial settlements to clean up the environment. The agency has secured millions of dollars from mines, an Army munitions depot and a wood treatment facility. But it completed just one action for petroleum pollution in decades. Even then, the office only had jurisdiction to pursue a small settlement because a tanker truck flipped on an icy road, **spilling refined gasoline and diesel into the Cimarron River**.

Legislators attempted to expand the office's authority in 2009, 2010, 2011, 2013 and again last year. All those efforts failed.

Ferrary, who **sponsored the 2023 bill** to grant the trustee more authority over petroleum and certain cancer-causing substances, said the oil and gas industry has "such strong lobbying that we have to negotiate whatever we are trying to do. It always seems to get negotiated down."

In a recent four-year period, the state's oil and gas industry spent $11.5 million to influence policy, in addition to employing dozens of lobbyists, according to **research from two government accountability nonprofits**.

"Lawmakers and regulators appropriately balance the need to hold industry accountable while also ensuring oil and gas operations remain viable," Frederick Bermudez, the vice president of communications for the New Mexico Oil and Gas Association, said in a statement. He added that Remnant is not a member of the trade group and that "bad actors in the industry should be held accountable."

Regulators argue they're underfunded and understaffed, while environmental activists point out agencies are sometimes tasked with simultaneously overseeing and advancing the industry. New Mexico records, for example, show that the Oil Conservation Division inspects roughly half the state's wells annually, but many go years without a visit. Meanwhile, it quickly greenlights requests to drill new wells, generally granting approval for more than 90%

of permits within 10 days.

The state does even worse at preparing for the industry’s decline. The division secured about 7% of the tens of millions of dollars of additional bonds it requested from companies in violation of idle well rules, according to a *ProPublica* and *Capital & Main* analysis of the agency’s data. (The division said some companies no longer need to hand over the requested bonds because they have since left their wells as orphans for the state to plug. The state has already labeled more than 1,700 wells as orphans.)

The Oil Conservation Division has “limited bandwidth” and has to triage enforcement, Fuge, its acting director, said, adding that a mix of enforcement actions and business decisions lead companies to plug many of their own wells. “We don’t prioritize inactive well actions when the chute’s too deep because we want to devote the resources that we have to other enforcement initiatives.”

“Ill-prepared for this last phase of life”

By the time regulators took notice of Remnant’s myriad violations and idle wells, it was too late.

Core to oil regulators’ power are bonds, the financial assurances oil companies must set aside to guarantee that wells are plugged. Proper cleanup is expensive, so when bonding levels are low, companies have no incentive to finish cleanup and retrieve their bonds.

To decommission a typical orphan well in New Mexico costs the state about $167,000, according to documents the Oil Conservation Division submitted to the U.S. Department of the Interior. That translates to an $11.8 billion shortfall between the potential future cleanup costs and bonds that companies set aside with the agency, *ProPublica* and *Capital & Main* found.

“The state of New Mexico is short,” Fuge said. “We don’t hold sufficient bonding to cover likely plugging liabilities.”

Fuge suggested the shortfall might be smaller, deferring to **an environmental group’s lower projection**. Elsewhere in state government, **the State Land Office in 2022 estimated** the gap between bonds and cleanup costs was $8.1 billion.

Based on the per-well cleanup costs Fuge’s agency submitted to the federal government, the wells belonging to Remnant and a related company could cost the state $67 million if they are orphaned. The companies have only set aside about $1.5 million in bonds across three state and federal agencies.

Under current New Mexico rules, companies only need to put up a single bond worth a maximum of $250,000 — no matter how many wells they have — with the Oil Conservation Division. The failed reform bill would’ve

Interior devotes billions to plugging old oil wells. Is it enough?

The agency under-counted abandoned wells by more than half, which means the effort covers only a fraction of the cost.

HCN High Country News

increased that cap to $10 million. The division can request additional bonds to cover the increased risk from idle wells, but when it asked Remnant and a related company for about $3 million, the operators put up less than a tenth of that and kept pumping oil.

Weak bonding rules and an unwillingness to take on the industry have created similar shortfalls across the nation.

The Pennsylvania General Assembly in the 1990s, for example, forced the state's oil regulators to hand back money that oil companies had set aside to plug wells drilled prior to 1985, which numbered in the tens of thousands of wells.

Oklahoma allows oil companies that prove they're worth at least $50,000 — about the price of one of the ubiquitous pickup trucks cruising the oil fields — to set aside no money to plug their wells.

And Kansas gives companies, no matter how many wells they own, the option of paying a flat $100 annual fee instead of setting aside a bond, as long as they have not committed recent infractions. Seven out of eight companies in the state take this route, leaving an average of less than $13 in bonds for each of the state's 150,000 unplugged wells. The state's estimated cleanup costs — which experts said may be low — would mean the state faces about a $1 billion shortfall between the bonds and plugging costs.

"Regulations that may have worked well enough in the past have left the public and the industry ill-prepared for this last phase of life for millions of old wells," Purvis, the petroleum reservoir engineer, said. "Left unchanged, current regulations and practices will continue to accrue liabilities that will ultimately fall on taxpayers."

"Left unchanged, current regulations and practices will continue to accrue liabilities that will ultimately fall on taxpayers."

All told, oil drillers have set aside only $2.7 billion in bonds with the 15 states that account for nearly all the country's oil and gas production and $204 million with the Bureau of Land Management, the main federal oil regulator. The expected cost to plug and clean up wells in those states is $151.3 billion.

ProPublica and *Capital & Main* obtained and analyzed more than a thousand pages of **states' applications for funding to plug orphan wells** as part of the Biden administration's Infrastructure Investment and Jobs Act. The documents reveal for the first time states' own estimates of the cleanup costs in a way that allows states to be compared.

"You can give us probably the entire infrastructure act funding — $4.7 billion — and we'd probably spend that in Pennsylvania," Kurt Klapkowski, head of the commonwealth's Office of Oil and Gas Management, told a national meeting of regulators in October.

Some states acknowledged that accumulated costs from unplugged wells are high but said they could be mitigated by additional money in the states' orphan well funds — which often contain several million dollars and were not included in this study — and by tools meant to ensure companies, rather than taxpayers, plug the wells. For example, Wyoming significantly increases the bonds required of operators when wells go idle.

"Wyoming is fully bonded to be protective of the wells" under state oversight, Tom Kropatsch, oil and gas supervisor of the Wyoming Oil and Gas Conservation Commission, said in an email, pointing to the fact that most wells that have been plugged in Wyoming were plugged by the industry, not the state. "The bonds we hold are adjusted on an ongoing basis as our agency conducts an annual bond review of each operator."

North Dakota regulators, with the luxury of a still highly profitable industry, have resources to more rigorously police oil. Lynn Helms, director of the North Dakota Department of Mineral Resources, said this includes enough inspectors to observe well plugging, determine whether idle wells require additional bonding and scrutinize proposed well transfers to smaller operators, which are "the biggest risk."

Helms said the state aims to cover as much as 10% of future plugging costs through bonds and orphan well funds, although his department is still working to reach that level.

Both North Dakota and Wyoming hold more bonds and face lower impending liability than New Mexico.

"When the bottom goes out of this oil and gas production economy, who's going to be left holding that bag?"

"When the bottom goes out of this oil and gas production economy, who's going to be left holding that bag?" New Mexico Commissioner of Public Lands Stephanie Garcia Richard asked.

"I got big-time screwed over"

In July 2019, less than four years after Gray, Stitzel and Gilmore began buying up wells, Remnant was in bad shape. Its wells were deteriorating and production was declining. The owners had made a costly gamble on an oil sale and the company's bank demanded payment on a debt, according to court testimony from Gray.

So Remnant employed a tactic that has saved the oil industry billions — **its owners filed for Chapter 11 bankruptcy protection** with a court in Texas.

The Bankruptcy Code is meant to protect jobs, creditors and the economy by allowing companies to stabilize during rough patches. But bankruptcy court is a key step in the industry's playbook, as it **has become an oil field escape hatch**, effectively allowing companies with aging wells to sell off valuable assets while orphaning wells in need of immediate cleanup. Companies can also stop the clock on many enforcement actions.

Between 2015 and 2021, 256 oil and gas producers entered bankruptcy protection across the country, carrying with them about $175 billion in debt, **according to Haynes and Boone**, a law firm that produced the most comprehensive research on oil field bankruptcies. (Haynes and Boone is representing *ProPublica* in several Texas lawsuits.)

Court records show the bankrupt Remnant companies owed millions of dollars to hundreds of creditors — oil field service companies, the New Mexico Taxation and Revenue Department, counties, banks, trucking companies and a local air conditioning and heating company.

But in the year leading up to the bankruptcies, court filings show, Remnant paid hundreds of thousands of dollars in consulting fees to companies belonging to at least two of the men who ran the company and cut numerous paychecks to a daughter, son, cousin and daughter-in-law of various executives.

In April 2020, unsecured creditors who were owed millions of dollars had the case converted to Chapter 7, meaning a trustee would take over, liquidate the company's assets and pay back creditors where possible.

Debts relating to cleaning up the environment or repaying labor "get pretty low priority" in bankruptcy cases, explained Josh Macey, a law professor at the University of Chicago who studies bankruptcy and reviewed *ProPublica* and *Capital & Main*'s findings. To Macey, one solution to unfavorable bankruptcy rules is bonds, as they're protected even in bankruptcy.

"Bonding requirements have not proven to be sufficient," he said, "but if they were, it would make bankruptcy irrelevant."

Arturo Carrasco was one of Remnant's unsecured creditors, meaning a long list of debts would have to be settled before he saw any money. Carrasco, now retired, owned Art's Hot Oil Services, an oil field maintenance company with a handful of drivers and trucks out of Lovington, New Mexico. By the time Remnant hired Carrasco's company to work on its wells, most were "already depleted," he said.

Remnant only paid him a little at a time and never the full amount it owed, Carrasco said.

Carrasco filed claims for more than $165,000 in the bankruptcy, according to court records, and that didn't include another $50,000 in unpaid expenses like fuel, he said. Concerned his company might go under, Carrasco worked "double time" to make up for the lost income. With no expectation of recovering money via the bankruptcy, he briefly fantasized about throwing a chain around Remnant's pump jacks and pulling them down.

"I got big-time screwed over," he said.

Graveyards of wells

Three months after the judge ordered that Remnant liquidate, a buyer called Acacia Resources LLC wired $402,000 to the trustee, **completing the purchase of Remnant's assets**.

The new company was run by familiar names — Stitzel and Gilmore, Remnant's former chief operating officer and president, **state records show**. Business filings and his LinkedIn profile suggest Gray left the venture to launch a helium and natural gas company.

"All they did was file bankruptcy. Then they went to the bank and bought it at a cheaper price, and they're still producing," Carrasco said. "How can that be allowed?"

Fuge, the New Mexico oil regulator, said the companies are the "subject of prime enforcement attention" but did not comment further. And a Bureau of Land Management spokesperson said Remnant had no outstanding violations and the agency was not preparing to forfeit the company's bonds.

Aerial view of oil and gas infrastructure in the western Permian Basin of New Mexico.
Bruce Gordon / SkyTruth

The details of Acacia's operations are murky. The on-the-ground situation doesn't always match New Mexico's data, while state records don't align with federal records.

But Remnant's business practices are similar to those of any number of undercapitalized drillers holding portfolios of old wells. So the State Land Office began a campaign to bring such operators into compliance to protect the state from shouldering the burden of even more orphan wells.

Buried amid pages of infractions in Remnant's files, agency staff noted that satellite imagery appeared to show a spill at a Remnant well in the Drickey Queen Sand Unit. In November, the agency wrote to Gray, Stitzel and others, demanding they begin plugging wells in the field.

Jaclyn McLean, an attorney representing Acacia, responded with a proposal — Acacia would plug a few wells per year and pay back some money it owed for pumping oil on expired leases if the state would renew those leases and reduce the amount the company owed. With Gilmore, who was a manager of both Remnant and Acacia, copied on the letter, McLean blamed prior management's "severe inaction" and promised that "the new management team seeks to maintain professionalism, integrity, and authenticity." (McLean did not respond to a request for comment.)

"Tell your client to get serious," the agency responded.

Still unplugged, Remnant's wells in the Drickey Queen Sand Unit stood eerily silent during a recent site visit, the bellowing and bleating of cattle the only sound as they grazed among the apparent orphans. At one of the pump jacks, which **had not drawn oil in more than eight years**, pieces of metal had corroded and fallen off. Lines used for collecting oil in preparation for sale lay in the dirt. They connected to nothing.

Methodology

To investigate what leads to oil and gas wells being orphaned, *ProPublica* and *Capital & Main* filed more than 55 public records requests with state and federal agencies and toured oil fields in New Mexico, Texas and California. We interviewed dozens of petroleum engineers, researchers, community members and government officials, including the leadership of oil agencies in Louisiana, North Dakota, Pennsylvania and elsewhere.

To determine the magnitude of the shortfall between cleanup costs and bonds, we needed to answer several questions: how many wells are unplugged, how much money have companies set aside in bonds and how much does it cost to plug and remediate a well. The analysis focused on the top 15 oil- and gas-producing states because, according to U.S. Energy Information Administration data, they accounted for 99% of the country's output in recent years. Those states are Texas, Pennsylvania, New Mexico, Oklahoma, North Dakota, Louisiana, Colorado, West Virginia, Ohio, Wyoming, Alaska, California, Arkansas, Utah and Kansas.

With **petroleum reservoir engineer Dwayne Purvis**, we analyzed data from energy software company **Enverus** to determine the number of unplugged wells in each state, conservatively defining them as either clearly active or in some stage of idling. We checked these figures against previous estimates, such as what **states self-reported to the Interstate Oil and Gas Compact Commission**.

To calculate plugging costs, we used the estimates that states reported to the U.S. Department of the Interior in their notices of intent to apply for Infrastructure Investment and Jobs Act funds. We checked these figures against states' next round of applications, Native American tribes' applications and hundreds of orphan well plugging contracts from across the country. The agreements showed the detailed mechanics of the work, such as where cement plugs were placed, how surface infrastructure was removed and what post-remediation environmental monitoring was completed. Plugging costs varied widely depending on the depth, condition and geography of the well, but costs ballooned to the high six figures or even the seven-figure range when projects faced unanticipated obstacles, such as cannonballs having been dropped into a well as an improvised plug, wells igniting and the need to tear up city streets to plug some wells.

For bonding figures, we obtained the 15 states' datasets of all active bonds tied to oil and gas well plugging, remediation and reclamation. We relied on **figures reported by the Government Accountability Office** for the value of bonds held by the Bureau of Land Management. We requested, but did not receive, that agency's data, and the Bureau of Indian Affairs didn't answer questions about bonds on tribal land. We didn't include other jurisdictions' bonds, as those are much smaller. (For example, New Mexico's State Land Office requires bonds but only holds $20,000 for Remnant's wells.)

To check our methodology, we gave a 10-member panel of petroleum engineers, law professors and former regulators an opportunity to comment on the findings. These experts have worked or currently work with the California Geologic Energy Management Division, the Bureau of Ocean Energy Management, Texas Christian University, the Carbon Tracker Initiative and other research organizations. They widely accepted the final methodology. The lead oil regulatory agency from all 15 states also had a chance to review the findings. Some states' data showed slightly different numbers of unplugged wells than Enverus' data, but we used the Enverus data because it is standardized and not all states provided well counts. Regulators also emphasized that bonds are an insurance policy not meant to cover 100% of the cost, that states won't have to plug every well because the industry will plug many and that other agencies also hold bonds.

When estimating the total revenue generated by Remnant's and Acacia's wells, we used New Mexico Oil Conservation Division data to tell us how much oil and gas each well produced. Because some production wasn't assigned a year, we worked with Purvis to model a likely production decline curve. We multiplied that by each year's oil and gas prices, mainly found in Energy Information Administration data, and adjusted that for inflation, using Bureau of Labor Statistics figures.

Finally, our emissions testing fieldwork was completed using a handheld **Bascom-Turner Gas Explorer Detector**. We consulted **Amy Townsend-Small**, a professor of environmental sciences at the University of Cincinnati, to formulate the testing plan. We checked the readings with the manufacturer, whose employees said they had never seen their equipment register such high levels. They gathered in an office to call our reporter and ask if he was all right (he was because he wore an acid gas and organic vapor respirator around the wells).

Mark Olalde is a ProPublica *reporter covering the environment in the Southwest. Before joining* ProPublica*, he wrote for* The Desert Sun, The Arizona Republic *and the* Center for Public Integrity.

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Graphics by ***Jason Kao****.* ***Mollie Simon*** *contributed research, and* ***Agnel Philip*** *contributed data reporting.*

Exhibit 33.01

This exhibit was not previously submitted in November 2023

Figure: 30 TAC §350.51(m)

Texas-Specific Soil Background Concentrations milligrams per kilogram (mg/kg)[1]	
Metal	Median Background Concentration (mg/kg)
Aluminum	30,000
Antimony	1
Arsenic	5.9
Barium	300
Beryllium	1.5
Boron	30
Total Chromium	30
Cobalt	7
Copper	15
Fluoride	190
Iron	15,000
Lead	15
Manganese	300
Mercury	0.04
Nickel	10
Selenium	0.3
Strontium	100
Tin	0.9
Titanium	2,000
Thorium	9.3
Vanadium	50
Zinc	30

[1]Source: “Background Geochemistry of Some Rocks, Soils, Plants, and Vegetables in the Conterminous United States”, by Jon J. Connor, Hansford T. Shacklette, *et al*., Geological Survey Professional Paper 574-F, US Geological Survey.

Exhibit 34.01

This exhibit was not previously submitted in November 2023

Closed-Loop Systems Provide Win-Win Benefits In Horizontal Shale Plays

HOUSTON–The oil and gas industry is focused like never before on maximizing returns on every dollar in the budget while simultaneously maximizing the value of field assets and elevating environmental, social and governance performance. That is a tall order, but what if there was a way for operating companies to economically address ESG concerns while also promoting long-term sustainability and operational profitability?

Closed-loop waste management is revolutionizing the oil and gas industry by offering a win-win ESG solution for the Eagle Ford and other shale plays. As the chief executive of The Panther Companies, I have seen firsthand the transformative power of closed-loop waste management systems. Indeed, these systems not only provide ESG and sustainability solutions, but they also benefit oil and gas operations' bottom line.

By reducing waste and minimizing the risk of environmental damage, closed-loop systems can help companies increase profitability and investor interest. In addition, they can foster goodwill with local communities and regulators by demonstrating a commitment to responsible resource development.

Of course, implementing closed-loop systems can come with its own set of challenges and considerations. But with the right technology and expertise, these challenges can be overcome, and the benefits are too significant to ignore.

I am proud to see closed-loop systems becoming a more widely adopted solution, including for shale operators seeking to improve their ESG standing.

Closed-loop systems help minimize the amount of waste that must be disposed of by treating, recycling and reusing it, which in turn reduces oil and gas operations' overall environmental impact. They also help prevent soil and water contamination by ensuring that drilling fluids and any associated waste are handled and disposed of in a responsible manner that minimizes environmental risks.

By helping mitigate the environmental impact of oil and gas operations, these systems also can improve profitability. A recent Eagle Ford project with a private operator provides a prime example of how closed-loop systems can benefit both the environment and profitability.

Since its 1985 founding, the operator has drilled more than 800 wells in the United States and abroad. The company currently focuses on acquiring and developing unconventional assets in the Eagle Ford trend, where it has implemented a closed-loop system for two horizontal wells in southern Fayette County, Tx.

The project's first well targeted the Lower Eagle Ford Shale with a 9,600-foot lateral. The second was a Lower Austin Chalk well with a 10,500-foot lateral. Both would represent record lateral lengths for the play area. To facilitate the closed-loop operations, The Panther Companies provided the mud products, state-of-the-art solids control equipment, and managed the haul-off and disposal for both horizontal wells.

By implementing a closed-loop system, the company was able to successfully drill the longest laterals in this portion of Fayette County, while also minimizing waste and reducing the environmental impact. This project is a testament to the power of innovation and collaboration in driving sustainable practices in our industry.

As seen in our recent partnership, closed-loop systems can set new standards for drilling efficiency and sustainability. We are committed to continuing to lead the industry toward more sustainable practices and working with companies to achieve their ESG goals.

Application Envelope

As more oil and gas companies look to improve their ESG standing and lower costs, closed-loop systems are likely to become an increasingly important tool. However, it is important to consider when these systems are the best option versus when other processes may be more suitable.

One of the primary advantages of closed-loop systems is the ability to treat, recycle and reuse drilling fluids, which can mean significant cost savings. Therefore, closed-loop systems make the most sense when a lot of drilling fluid is being used and there are limited disposal options. It is much more economical to treat and reuse the fluid than to constantly dispose of it and bring in new fluids.

Additionally, closed-loop systems are ideal for areas where water resources are limited, since the systems significantly reduce the amount of freshwater that is needed for drilling operations. This is particularly important in regions prone to droughts or in which water is scarce.

On the other hand, closed-loop systems may not be the best option for every drilling operation. For smaller jobs that do not require much drilling fluid, traditional disposal methods may be more cost-effective. Moreover, if a site has limited space or infrastructure, it may not be feasible to set up a closed-loop system.

In these cases, it is important to evaluate other waste management options and consider each method's environmental impact.

For a private producing company with Gulf Coast operations, the decision to use a closed-loop waste management system typically is determined by the well type and its geographical area. As a company that focuses on conventional onshore oil and gas exploration, the operator tends to opt for closed-loop systems when the well requires a weighted mud system with barite or an oil-based mud system. Other factors that come into play when choosing the disposal method include surface restrictions on land farming and environmental risks such as wetlands, waterways or densely populated areas.

Generally, the operator tends to use closed-loop systems more than 90% of the time in Texas and 100% of the time in Louisiana because of state land farming regulations and litigation concerns.

Shale Oil Challenges

Oil-based mud is a common choice for drilling in the Eagle Ford because it promotes higher penetration rates and wellbore stability, especially in challenging geological formations. However, this preference adds another layer of complexity with regard to waste disposal.

Therefore, our upstream partner in the Eagle Ford prefers closed-loop systems for most projects because they ensure proper waste disposal and reduce the company's long-term concerns. Even so, the benefits of closed-loop systems extend far beyond waste disposal.

By minimizing the volume of waste in need of disposal, operators can reduce their costs significantly. Additionally, reclaiming and reusing as much drilling fluid as possible improves drilling operations' economic efficiency, especially in times of high diesel prices. In some areas of the Eagle Ford, for instance, the cost of a barrel of oil-based mud is around $175, which makes it a valuable resource that is worth conserving.

Panther uses state-of-the-art solids control equipment to dry cuttings and reclaim all possible fluids, minimizing the haul-off on both fluids and solids. Our equipment also can recycle much of the used oil-based mud.

This gets to the heart of what we consider the real reason behind closed-loop systems: Reclaim as much as possible; haul off as little as you can. Nevertheless, closed-loop systems also provide other benefits, and we believe that these systems are the future of the oil and gas industry, which makes us proud to be at the forefront of this technology.

Modern Closed-Loop

The upfront costs of implementing a closed-loop system typically are offset by reduced hauling and disposal costs. Additionally, the overall efficiency of drilling operations may improve with closed-loop systems and trim costs further.

State-of-the-art solids control equipment also makes closed-loop systems better for drilling operations. Not only does this equipment effectively separate drilling solids from drilling fluid, but it also ensures that the fluid can be reused in the drilling process, reducing the need for constant disposal and fresh makeup fluid.

By minimizing waste and limiting the discharge of drilling fluids and solids into the environment, closed-loop systems are a critical tool for shrinking drilling operations' environmental impact. In addition to the environmental benefits, closed-loop systems also improve drilling projects' efficiency and cost-effectiveness.

Furthermore, today's solids control equipment is crucial to the effectiveness of closed-loop systems. With equipment such as shale shakers, hydrocyclones and centrifuges, solids control ensures that each stage removes progressively smaller particles from the drilling fluid. Removing solids and other materials can extend fluid life, improve drilling efficiency and reduce drilling operations' environmental impact.

With a growing emphasis on environmental sustainability, many production companies are turning to closed-loop waste management systems to minimize drilling waste and, as a result, reduce their volumes of offsite waste disposal. This can lower the risk of accidents and spills during transportation. They also can help conserve water and other depletable resources that would be necessary for new treatment processes.

Other benefits of closed-loop systems include lessening the need for human resources dedicated to waste hauling and disposal, allowing personnel to focus on other areas of the operation. This can improve safety and worker satisfaction, as well as reduce waste disposal's environmental impact. Additionally, closed-loop systems often have built-in safety mechanisms, such as automated monitoring and control, which further improve safety and environmental performance.

Overall, closed-loop systems offer a unique combination of environmental and financial benefits that make them a game-changer for the oil and gas industry.

Win-Win Solution

The oil and gas industry is evolving constantly, and as we navigate a changing landscape, closed-loop systems offer a compelling solution for producing companies looking to balance economic, social and environmental concerns.

By embracing these systems, companies not only can reduce their environmental footprints, but also improve their social and governance standing, demonstrating a responsible approach to conducting operations. Their adoption also may have a positive impact on investor attitudes toward the oil and gas industry.

As more investors prioritize ESG factors in their decision-making processes, companies that demonstrate a commitment to sustainability and responsible operations may be better positioned to attract investment. Moreover, the operational efficiency and financial benefits of closed-loop systems cannot be overlooked.

Closed-loop systems allow for the treatment, recycling and reuse of drilling fluid, thereby reducing offsite waste disposal. This, in turn, leads to significant cost savings for oil and gas companies, making their operations more profitable and efficient.

As the industry continues to evolve and face new challenges, adopting innovative technologies and practices that promote sustainability and responsible operations will be essential for success. Closed-loop systems are a win-win for the industry, the environment and local communities.

Exhibit 34.02

This exhibit was not previously submitted in November 2023

Pit-less in the Permian - Permian Basin Oil and Gas Magazine

PBOG

Closed-loop drilling fluids systems shrink industry footprint.

By Julie Anderson

Perhaps it's time to change the conversation, at least for a bit.

There's no denying the volatility, uncertainty, and gravity of declining oil prices, especially when it results in job loss. With that said, how about taking a look at the landscape in search of something positive, a project or technology or system that speaks to progression, not recession? We took a look around, and what we didn't see led to this story, perhaps reinforcing the adage, "less is more."

Shrinking Footprint

Most everyone has seen the big earthen pits that are usually dug and constructed at a drilling site, noted Jeff Dennis, owner and managing partner at CR 90 Manufacturing in Midland, http://www.cr90.com/.

At a typical oil and gas drilling site, drilling fluids are circulated through the wellbore, and then the fluids and drill cuttings are deposited in a reserve pit dug near the wellbore, as described by GN Solids Control. In other words, this pit is used to hold discarded drilling fluids and waste.

In fact, Ken Goldsmith, president and owner of Mudsmith Ltd. in Midland, http://www.mudsmith.com/, remembers back 35 years ago when nearly 100 percent of the Permian Basin's drilling rigs used these earthen pits, many without plastic linings.

Sam Ledbetter, an experienced drilling fluids engineer, refers to them as "cuttings pits" dug on location to hold drill cuttings.

Mud pits, reserve pits, earthen pits, cuttings pits—regardless of the name, we're seeing fewer across our landscape, and here's why: the closed-loop drilling system. While the technology itself is not new, the practice is catching on as improved systems continue to come online.

"Closed-Loop" Defined

Generally speaking, in a closed-loop drilling fluids system, the earthen reserve pit is replaced with a series of storage tanks, which separate liquids and solids, according to GN Solids Control, http://oilfield.gnsolidscontrol.com/closed-loop-drilling-fluids-system/. Solids-control equipment (shale shaker, mud cleaner, decanter centrifuge) and collection equipment (vacuum trucks, roll-off boxes,) minimize the amount of drilling waste and cuttings that require disposal and maximize the amount of drilling fluid recycled and reused in the drilling process. The wastes created are typically transferred off-site for disposal at injection wells or oilfield waste disposal facilities.

Part of the closed-loop drilling process is trying to recover as much of the drilling fluid as possible off of the drill cuttings, Ledbetter detailed. This can be as simple as "shaking or spinning" the cuttings before they are sent to disposal, or as complicated as recovering the drilling fluid off the cuttings and then separating the liquid from the solids in the drilling fluid.

Companies that supply closed-loop systems are constantly evaluating and integrating technology to make closed-loop systems function better, explained Dennis, who has been building these systems for the past several years.

"For instance, variable speed drives are used to operate centrifuges, pumps, and augers to ensure they turn at just the right speed to get the job done," Dennis continued.

"I first saw a closed-loop drilling system nearly 25 years ago," Ledbetter recalled. "It has become the norm for drilling operations due to environmental concerns of leaving drill cuttings on location and cost savings of recovering as much of the drilling fluid from the cuttings as possible."

Closed-loop drilling systems are also referred to as "closed-mud" or "pit-less" systems.

Pit-less in the Permian

"In the Permian Basin, most wells are commonly drilled with a fluid-circulating system, although some wells are drilled with an air-circulating system," Goldsmith said. Properly designed drilling fluids are circulated through the drill bit and up the annulus between the drill pipe and the open-hole wall, carrying drilled cuttings to the surface to be properly disposed of.

"Since our region is predominantly flat, barren, desert land, open-pit drilling fluids-circulating systems have been permissible and the least expensive method of separating, storing, and disposing of drilled cuttings and used drilling fluids, i.e. drilling fluids waste," Goldsmith explained. "So long as the drilling fluids system is water-based, biodegradable, and environmentally friendly, open-pit systems have been acceptable in our region.
"When a small location footprint, and/or a less-than-environmentally friendly drilling-fluid system is utilized, a closed-loop solids-control system is utilized," Goldsmith continued. While open-pit systems utilize high volumes of drilling fluids and depend on retention time to allow solids to fall out in the settling pits, closed-loop systems utilize lesser volumes of drilling fluids, and mechanical solids-removal methods are employed.

The technology is not new, Goldsmith said; after all, offshore rigs have always utilized closed systems. However, Goldsmith cites three "primary drivers" that have brought closed loop systems into play in the Permian:

1. Politics: At one point in an area of the Permian Basin, it was determined that open pit systems had a negative environmental impact on the land, and regulatory rulings were put into place that made it difficult, if not impossible, for operators to utilize open-pit drilling systems," Goldsmith stated. The alternative was to utilize closed-loop solids-control systems and haul all drilled cuttings and drilling fluids waste to designated disposal systems.
2. Horizontal Drilling: Horizontal drilling in our region has led to an evolution away from inexpensive, environmentally friendly water-based mud systems to more expensive, diesel oil-based mud systems, which are not able to be disposed of in open pits when the drilling phase is completed.
3. Cost: While open-pit drilling is still considered the least expensive method of solids-control and drilling fluids waste disposal for vertical drilling in the Permian, closed-loop systems can and do provide a cost-effective alternative for keeping drilling fluid volumes low and containing wastes with the least possible environmental impact.

Cost of Closed-Loop

"The initial cost of utilizing a typical closed-loop system is the equipping of drilling rigs with steel working pits, or sufficient tankage to contain the entire drilling fluids system with no assistance from open earthen pits," Goldsmith said. Additional costs include equipping the rigs with sufficient mechanical solids removal equipment, such as high volume shale shakers, centrifuges, cuttings dryers, etc. Though occasionally owned by the drilling contractor, this equipment is more commonly rented from service companies that specialize in the management and operation of closed-loop solids-control systems.

Costs vary depending on what equipment is being supplied, Dennis suggested, but in today's market utilizing a closed loop drilling system runs about $2,500 per day.

Initial costs would vary depending on the process being used, Ledbetter said, but the daily cost would be somewhere between $2,500-$4,000 per day depending on the complexity of the system being used in the closed-loop drilling process.

Benefits of Closed-Loop Systems

"A closed loop drilling system provides a cost-effective and efficient means for extracting solids from drilling fluid," Dennis said. There are many benefits in using a closed loop system as opposed to a traditional reserve pit, he continued, but, "probably the biggest cost benefit is the reduction of a driller's liability." Once the drilling is completed, all of the used drilling fluid is hauled off and properly disposed of.

A closed-loop system can also save water, Dennis said. It's been estimated that a closed loop drilling system will only use 20 percent of the water that would be required to drill a well with a reserve pit system.

"The location footprint is also much smaller with a closed-loop system," Dennis said. "This is great when drilling is being performed in close quarters such as residential areas."

"Aside from reducing the environmental impact of disposing of drilling fluids waste on each drilling location, properly designed and managed closed systems lead to enhanced solids removal, easier and less costly management of drilling fluids properties, earlier detection of gas kicks or water flows, and reduced costs of drill site preparation," Goldsmith said.

Ledbetter cited the main benefit as environmental.

"You eliminate a cuttings pit on location and send the drilled cuttings and used mud to a regulated disposal site," he said. "You also reduce the amount of waste being sent to the landfill using a closed-loop drilling system. With that said, there are also cost savings that go along with the environmental benefits."

Operators reduce the cost of the drilling fluid by recapturing as much of the fluid as possible and reusing it on location, Ledbetter offered.

"If you are using oil-based mud, this can be a substantial savings even at today's oil prices," he said. There's also the reduction in the cost of waste disposal by recycling as much of the drilling fluid or the liquid as possible. This reduces the amount of bulking material needed to dry the cuttings prior to sending them to a landfill.

"The less material sent to the landfill, the greater the savings," Ledbetter emphasized.

One of the side benefits is that using the closed-loop system forces the mud engineer and drilling engineer to do better tracking of the volumes of drilling fluid being used and the amount of waste being generated on location, Ledbetter added.

"Better tracking means keeping a closer eye on costs," he said.

When it comes to the cost/benefit analysis, the Railroad Commission of Texas offered the following scenario:

Closed-Loop Drilling Fluid System

Problem: A small independent operator was concerned about the volume of drilling waste in conventional reserve pits at his drilling locations. Waste management costs were a concern, as well as the costs associated with impact on adjacent land due to pit failures. The operator was concerned about the potential for surface water or groundwater contamination and the associated potential liabilities.

Solution: The operator was drilling relatively shallow wells in normally pressured strata. Because the drilling plan was relatively simple, the operator investigated the feasibility of using a closed-loop drilling fluid system for these wells. The use of a closed-loop system eliminated the need for a conventional reserve pit. The operator negotiated with drilling contractors to obtain a turnkey contract, which required the drilling company to use a closed-loop system and take responsibility for recycling the drilling fluid waste.

Benefits: The turnkey contract was incrementally more expensive. However, because of reduced drill site construction and closure costs, reduced waste management costs, and reduced surface damage payments, the operator realized a savings of about $10,000 per well. Also, the operator reduced the potential for environmental impact and associated potential liability concerns.

A Lesson in Gravity and a Paradigm Shift

Some 35 years ago, it occurred to Goldsmith that those who designed drilling rigs were focused on the drilling rig versus the drilling fluid.

"Their primary objective was to build efficient drilling rigs, and the drilling fluids, or mud system, was a secondary objective," Goldsmith concluded. "Even the very best mud systems I've seen on drilling rigs fall short in many areas. Mixing and maintaining mud is what makes roughnecking rough!"

Goldsmith launched his career in drilling fluids back in 1980 with Baroid Drilling Fluids in Snyder and opened his Midland Mudsmith office in 1999. Since that time, he has seen the industry evolve from rigs that utilized nearly 100 percent earthen pits, many not even plastic lined, with primitive or no mechanical solids removal devices, to modern day rigs with multimillion dollar closed-loop steel pits outfitted with sophisticated mechanical solids-removal equipment.

"Eventually, we at Mudsmith evolved from horizontal, rectangular, open-topped pits, to vertical, round, cone-bottomed, closed-top tanks," Goldsmith said. These tanks take advantage of an optimized use of gravity.

Mud is simply a mixture of solids and liquids, and gravity insists that solids fall downward. Thus, vertical, round, cone-bottomed tanks are more efficient.

Nevertheless, almost all drilling contractors have invested in horizontal mud systems, so the paradigm shift to vertical tanks is a process. Meanwhile, using vertical tanks as supplemental mixing equipment at the rig has caught on, "and we can pretty much rent them as fast as we can build them," Goldsmith said.

"Since Mudsmith's tanks are symmetrical, they can be manifolded together in a series, and with the addition of a few solids-control tanks, a complete horizontal rig pit system can be replaced with what Mudsmith calls a Pit-less Pad-Drilling Fluids System," Goldsmith said.

With so many rigs stacking, operators typically send oil-based mud back to their vendors, although mud vendors all have limited storage.

"Imagine you have 10 [or more] horizontal rigs stacked, and each rig needs to send back some 2,000 bbls of oil mud to be stored," Goldsmith offered. "It doesn't take long for storage to become a big concern and a big cost for either the mud vendor or the operator. This problem has created an opportunity for our vertical, round, cone-bottomed mud storage tanks equipped with circulating pumps."

"A new paradigm was required to arrive at a cost-effective solution," Goldsmith said. The old paradigm is as follows: closed-loop systems require a retrofit of most rigs; however, the Pit-less Pad-Drilling System does not require a retrofit as everything required is provided by one source.

One-hundred percent of all solids contained in upright settling tanks can be removed by trucks with no contamination to the land or groundwater. Benefits include:

- Eliminates soil/groundwater contamination
- Reduces time and construction costs
- Reduces clean-up, or remediation costs
- Much smaller location footprint
- No cuts into pipelines
- Saves birds, wildlife, and livestock
- Reduces water consumption
- Reduces waste of mud products
- Improves relationship with surface owners

"The key is the vertical tanks," Goldsmith concluded. While typical earthen reserve pits and steel working pits are horizontal and open-topped, this system harnesses enhanced use of gravity by stacking drilling fluid volumes up vertically.

Julie Anderson, based in Odessa, is editor of County Progress Magazine, and is well known to many readers of PBOG as the former editor of this magazine.

Exhibit 34.03

This exhibit was not previously submitted in November 2023

Closed Loop Drilling Fluid System

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Solution: The operator was drilling relatively shallow wells in normally pressured strata. Because the drilling plan was relatively simple, the operator investigated the feasibility of using a closed-loop drilling fluid system for these wells. The use of a closed-loop system eliminated the need for a conventional reserve pit. The operator negotiated with drilling contractors to obtain a turn-key contract that required the drilling company to use a closed-loop system and take responsibility for recycling the waste drilling fluid.

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Exhibit 34.04

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Costs for Drilling The Eagle Ford

Rigzone Staff

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While there have been instances when wells were drilled in as little as 15 days, a reasonable expectation for the time required to drill a well in the Eagle Ford is around one month. Based on a survey of operators in the region, drilling & completion cost per well are ranging from $5.5 to $9.5 million. The wide variation for drilling costs is dependant on such factors as the well's targeted depth, lateral lengths, number of laterals, and the number of frac stages deployed. Below we have provided a summarized estimate of both drilling and completion costs in the region.

Typical Eagle Ford Well Budget

	($ thousands)
Drilling	
Set Up Costs	215
35 Rig Days @ 20k/d	700
Fluids, Chemicals, Transportation & Fuel	270
Services & Rental Equipment	540
Bits, Expendable Equipment & Misc.	60
Labor, Engineering & Overhead	70
Casing and Other Tangibles	190
Contingencies	240
Plugging & Abandonment	100
Sub-total for Drilling	**$2,385**
Completion	
Set Up	35
Rig & Daywork	115
Fluids, Chemicals, Transportation & Fuel	66
Services & Rental Equipment	208
Formation Stimulation	2,760
Expendable Equipment & Misc.	19
Casing and Other Tangibles	430
Contingencies	325
Sub-total for Completion	**$3,958**
Total Drilling and Completion Budget	**$6,343**

Currently, operators are implementing between 15 to 20 frac stages per well drilled in order to optimize reservoir recovery. This higher number of frac stages undertaken (relative to practices one year ago) is placing a slight bottleneck on completions and is fostering an environment for price escalation. Based on this environment, adding a 10% to 15% premium to our price estimates above (from early 2011 observations) may be more indicative of what operators will spend this summer to drill & complete an Eagle Ford well.

A majority of wells being drilled in the Eagle Ford are targeting depths between 9,000 to 16,000 feet, with horizontal laterals ranging from 5,000 to 7,000 feet. Currently, target depths for E&P firms drilling for oil are greatest in Live Oak County at 13,250 feet versus an average target depth of 11,550 feet across all counties drilling for oil.

For natural gas, the target depths are largest in Karnes County at an average of 16,200 feet versus the overall drilling average in the Eagle Ford of 12,800 feet. In aggregate, across all Eagle Ford counties, the targeted average depth for drilling either oil or natural gas is 12,200 feet.

Average Eagle Ford Well Depths By County (feet)

Average Eagle Ford Well Depths By County (feet)

	Gas	Oil	Average
ATASCOSA	12,653	12,667	12,660
BEE	14,000		14,000
DEWITT	15,611		15,611
DIMMIT	8,900	9,237	9,092
DUVAL	3,500		3,500
FRIO		9,982	9,982
GONZALES		13,093	13,093
KARNES	16,167	12,910	13,354
LA SALLE	12,036	10,039	11,196
LIVE OAK	13,163	13,250	13,180
MAVERICK		3,500	3,500
MCMULLEN	13,478	13,200	13,379
WEBB	12,845		12,845
WILSON		11,542	11,542
ZAPATA	9,800		9,800
ZAVALA	6,500	9,000	8,167
Grand Total	**12,803**	**11,550**	**12,220**

Source: Schlumberger Smith Bits STATS

Increased production rates via innovative technologies were recently documented by Petrohawk. In 12 wells where the HiWay fracturing technique (provided by Schlumberger) was compared to nine other wells (fractured using a Hybrid design), Petrohawk found significant flow improvements in the HiWay wells. Specifically, the HiWay wells have 32% higher flow rates and 42% higher pressure after 90 days of production. All the wells were choked similarly (18/64") and all were from the same field (Hawkville). For 2011, Petrohawk estimates each well at its Hawkville field will cost approximately $7.5 million, assuming laterals span 5,500 feet.

HiWAY vs. Hybrid Frac Comparison

Frac Design	Average 90-Days Production: Number of Wells	Average 90-Days Production: Rate (Mcfe/d)	Average 90-Days Production: Pressure (#)	Choke (64ths")
Hybrid	9	5,366	3,207	18
HiWAY	12	7,107	4,541	18
% Increase		**32%**	**42%**	

Source: PetroHawk

According to Schlumberger Smith Bits STATS, the U.S. land rig count has grown by 228 rigs or 16% over the past year to 1650 rigs. Growth from Texas alone accounted for nearly 80% of this increase as the Lone Star count improved by 181 rigs or 33% year-over-year to 736 rigs. Furthermore, rapid expansion in the Eagle Ford was the source of over half of Texas' growth during the last twelve months.

The rig count in this region more than doubled to 174 rigs; a 94 rig increase from activity levels one year ago when 80 rigs were drilling in the 17 main counties encompassing the play. As of last week, the Eagle Ford rig count has advanced 20 rigs or 13% versus the March 11, 2011 count (the last time we wrote about the region). This current upward trend contrasts the overall land rig count in the U.S. that has fallen 3% since March 11th, 2011.

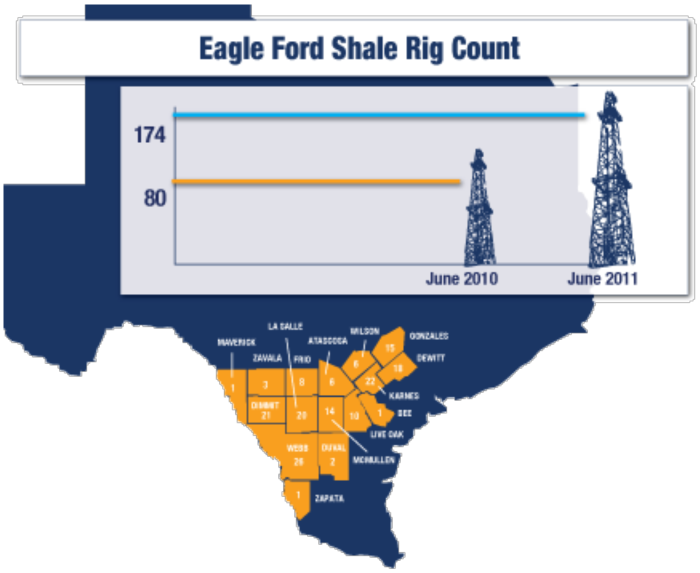
Stratigraphical Look at Eagle Ford Well

Under Ground Sources of Drinking Water	to 800'	
Miocene	800' to 2500'	Two layers of steel casing and two layers of cement from surface to 2,500'
Upper Eocene	2500' to 5000'	One layer of steel casing and one layer of cement
Eocene Wilcox Sandstone	5000' to 9900'	Top of cement at approximately 6,700'
Midway Shale	9,900' to 10,600'	

Upper Cretaceous	10,600' to 11,900'	Steel casing and one layer of cement to approximately 11,400'
Anacacho Limestone and Austin Chalk	11,900' to 12,200'	
Eagle Ford Shale	12,200' to 13,500'	Fracture Zone
Buda Limestone	+13,500'	

Source: Petrohawk

Observations of the Maverick Basin's stratigraphic column place the Eagle Ford Shale packed between the Anacacho Limestone/Austin Chalk (above) and the Buda Limestone (below) at more than 2 miles below the Earth's surface. The 17 primary counties that span the Eagle Ford in Texas form a swath from the border with Mexico stretching in a Northeastern triangle to the outskirts of San Antonio.



We have provided a table with ten of the leading land holders. These ten companies control 3.1 million acres across the Eagle Ford Shale in South Texas. A newer entrant into the region, Marathon, only recently spudded its first well in the region. However, with its $3.5 billion acquisition of Hilcorp's assets in the formation, Marathon has jumped several notches in size rankings and will likely be one of the leading players for several year's to come. Currently, EOG is the largest producer in the Eagle Ford and is also the largest land holder with nearly 550,000 acres. To date EOG has had a 100% success rate with wells drilled in the region.

Major Players With Acreage & Rigs In Eagle Ford Shale

		Rigs	
Operator	Acres	Budgeted 2011	Currently Drilling
EOG Resources	545,000	18	23
Chesapeake	450,000	17	17
Petrohawk	332,300	13	14
Newfield	335,000	3	2
Anadarko	300,000	10	10
Marathon/Hilcorp	285,000	NA	8
SM Energy	250,000	6	2
ConocoPhilips	220,000	13	14
Murphy E&P	220,000	6	3
El Paso	170,000	4	4
Percentage of Total Rig Count			**56%**

Source: Company reports

Exhibit 34.05

This exhibit was not previously submitted in November 2023

Independent Statistics & Analysis
U.S. Energy Information Administration

Trends in U.S. Oil and Natural Gas Upstream Costs

March 2016

This report was prepared by the U.S. Energy Information Administration (EIA), the statistical and analytical agency within the U.S. Department of Energy. By law, EIA's data, analyses, and forecasts are independent of approval by any other officer or employee of the United States Government. The views in this report therefore should not be construed as representing those of the Department of Energy or other federal agencies.

Contents

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Summary

The profitability of oil and natural gas development activity depends on both the prices realized by producers and the cost and productivity of newly developed wells. Prices, costs, and new well productivity have all experienced significant changes over the past decade. Price developments are readily observable in markets for oil and natural gas, while trends in well productivity are tracked by many sources, including EIA's Drilling Productivity Report which focuses on well productivity in key shale gas and tight oil plays.

Regarding well development costs, there is a general understanding that they are sensitive to increased efficiency in drilling and completion, which tends to lower costs, shifts towards longer wells with more complex completions, which tends to increase them, and prices for oil and natural gas, which affect markets for drilling and completion services through their effect on drilling activity. However, overall trends in well development costs are generally less transparent than price and productivity trends. Given the role of present and future cost trends to determining future trajectories of U.S. oil and natural gas production under a range of possible future price scenarios, it is clearly important to develop a deeper understanding of cost drivers and trends.

To increase the availability of such cost information, the U.S. Energy Information Administration (EIA) commissioned IHS Global Inc. (IHS) to perform a study of upstream drilling and production costs. The IHS report assesses capital and operating costs associated with drilling, completing, and operating wells and facilities. The report focuses on five onshore regions, including the Bakken, Eagle Ford, and Marcellus plays, two plays (Midland and Delaware) within the Permian basin[1], as well as the offshore federal Gulf of Mexico (GOM). The period studied runs from 2006 through 2015, with forecasts to 2018.

Among the report's key findings are that average well drilling and completion costs in five onshore areas evaluated in 2015 were between 25% and 30% below their level in 2012, when costs per well were at their highest point over the past decade.

Based on expectations of continuing oversupply of global oil in 2016, the IHS report foresees a continued downward trajectory in costs as drilling activity declines. For example, the IHS report expects rig rates to fall by 5% to 10% in 2016 with increases of 5% in 2017 and 2018. The IHS report also expects additional efficiencies in drilling rates, lateral lengths, proppant use, multi-well pads, and number of stages that will further drive down costs measured in terms of dollars per barrel of oil-equivalent ($/boe) by 7% to 22% over this period.

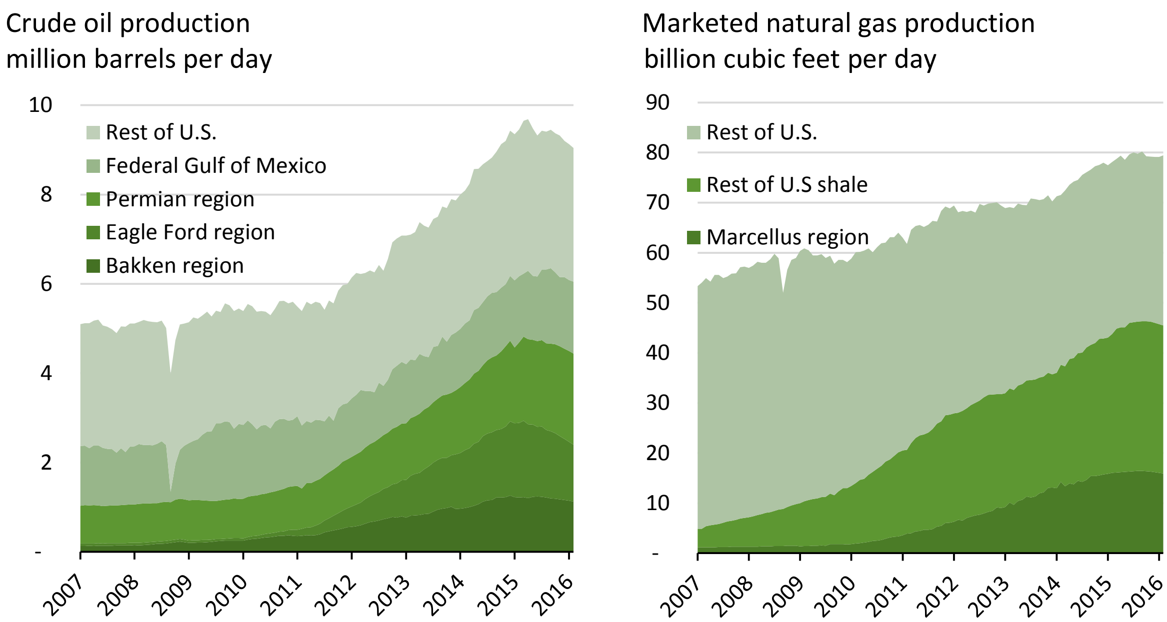
EIA is already using the observations developed in the IHS report as a guide to potential changes in near-term costs as exploration and production companies deal with a challenging price environment.

[1] The Bakken is primarily located in North Dakota, while the Marcellus is primarily located in Pennsylvania. The Eagle Ford and the two Permian plays (Midland and Delaware) are located in Texas.

Onshore costs

Costs in domestic shale gas and tight oil plays were a key focus of EIA's interest given that development of those resources drove the major surge in crude oil and natural gas production in the United States over the past decade, as shown in Figure 1. The IHS report documents the upstream costs associated with this growth, including increases associated with the demand for higher drilling activity during expansion and decreases during the recent contraction of drilling activity.

Figure 1. Regional shale development has driven increases in U.S. crude oil and natural gas production



Source: U.S. Energy Information Administration *Drilling Productivity Report* regions, *Petroleum Supply Monthly*, *Natural Gas Monthly*
Note: Shale gas estimates are derived from state administrative data collected by DrillingInfo Inc. and represent the U.S. Energy Information Administration's shale gas estimates, but are not survey data.

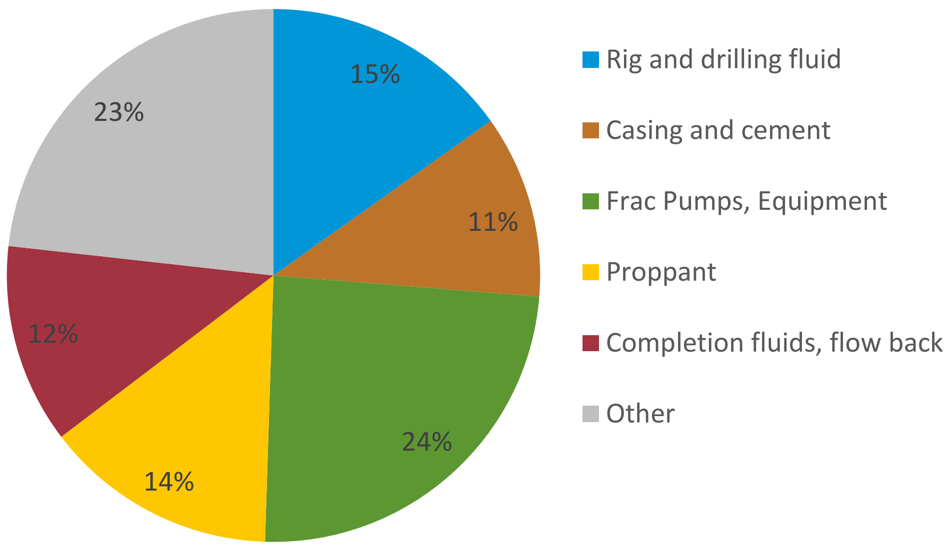
The IHS report considers the costs of onshore oil and natural gas wells using the following cost categories: land acquisition; capitalized drilling, completion, and facilities costs; lease operating expenses; and gathering processing and transport costs. Total capital costs per well in the onshore regions considered in the study from \$4.9 million to \$8.3 million, including average completion costs that generally fell in the range of \$ 2.9 million to \$ 5.6 million per well. However, there is considerable cost variability between individual wells.

Figure 2 focuses on five key cost categories that together account for more than three quarters of the total costs for drilling and completing typical U.S. onshore wells.[2] **Rig and drilling fluids** costs make up 15% of total costs, and include expenses incurred in overall drilling activity, driven by larger market conditions and the time required to drill the total well depth. **Casing and cement** costs total 11% of total

[2] Typical U.S. onshore wells are multi-stage, hydraulically fractured, and drilled horizontally. The costs identified relate, in part, to the application of those technologies.

costs, and relate to casing design required by local well conditions and the cost of materials. **Frac Pumps, Equipment** costs make up 24% of total costs, including the costs of equipment and horsepower required for the specific treatment. **Proppant** costs make up an average of 14% of total costs and include the amount and rates for the particular type of material introduced as proppant in the well. **Completion fluids, flow back** costs make up 12% of total costs, and include sourcing and disposal of the water and other materials used in hydraulic fracturing and other treatments that are dependent on geology and play location as well as available sources.

Figure 2 Percentage breakdown of cost shares for U.S. onshore oil and natural gas drilling and completion

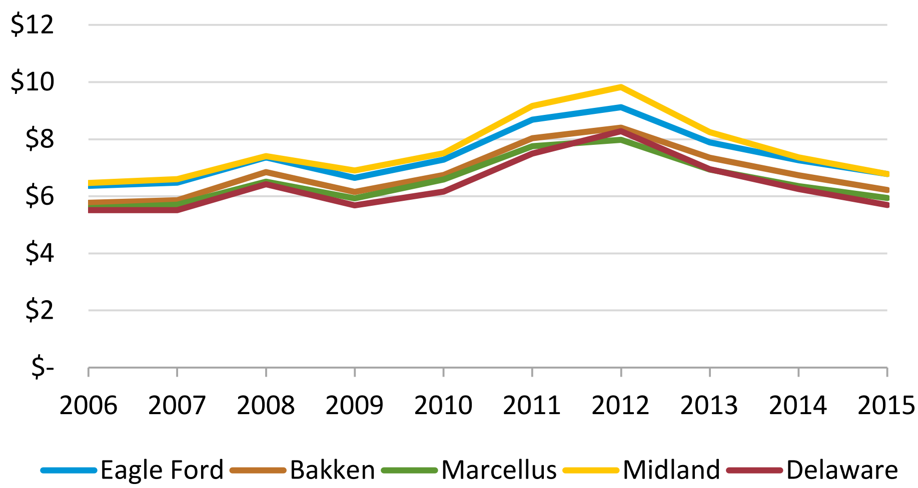


Source: IHS *Oil and Gas Upstream Cost Study commissioned by EIA*

Over time, these costs have changed. For example, drilling and completion cost indices shown in Figure 3 during the period when drilling and drilling services industries were ramping up capacity from 2006 to 2012 demonstrate the effect of rapid growth in drilling activity. Since then, reduced activity as well as improved drilling efficiency and tools used have reduced overall well costs. Changes in cost rates and well parameters have affected plays differently in 2015, with recent savings ranging from 7% to 22% relative to 2014 costs.

Figure 3. Average well drilling and completion costs for the 5 onshore plays studied follow similar trajectories

Cost by year for 2014 well parameters
$ million per well



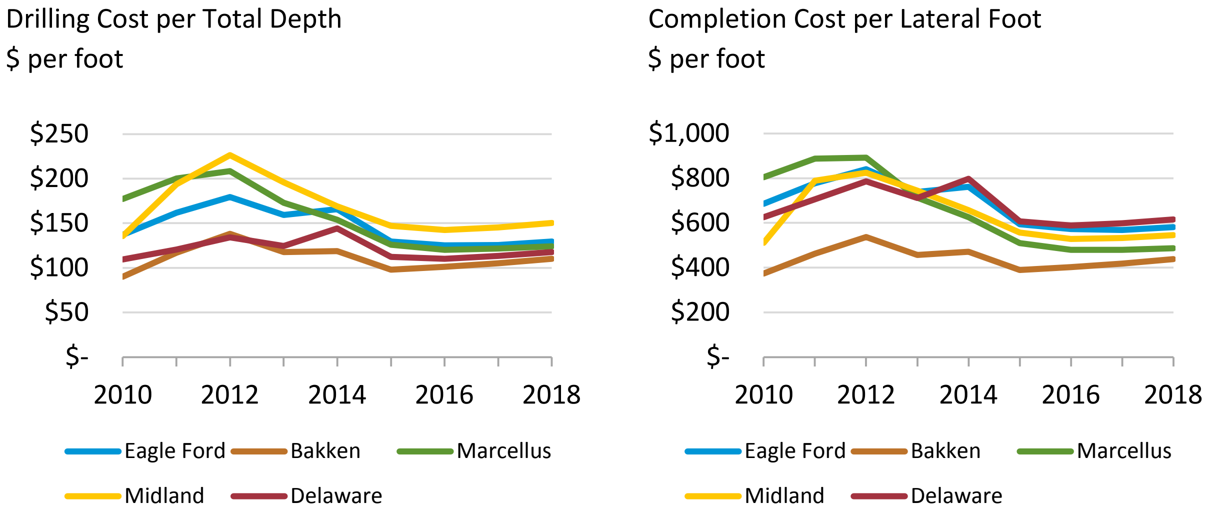
Note: Midland and Delaware are two plays within the Permian basin, located in Texas and New Mexico
Source: IHS *Oil and Gas Upstream Cost Study commissioned by EIA*

The onshore oil and natural gas industry continues to evolve, developing best practices and improving well designs. This evolution resulted in reduced drilling and completion times, lower total well costs, and increased well performance. Drilling technology improvements include longer laterals, improved geo-steering, increased drilling rates, minimal casing and liner, multi-pad drilling, and improved efficiency in surface operations. Completion technology improvements include increased proppant volumes, number and position of fracturing stages, shift to hybrid fluid systems, faster fracturing operations, less premium proppant, and optimization of spacing and stacking. Although well costs are trending higher, collectively, these improvements have lowered the unit cost of production in $/boe.

The cost variations across the studied areas arise primarily from differences in geology, well depth, and water disposal options. For example, Bakken wells are the most costly because of long well lengths and use of higher-cost manufactured and resin coated proppants. In contrast, Marcellus wells are the least costly because the wells are shallower and use less expensive natural sand proppant. Figure 4 shows, by region, how costs for well vertical and horizontal depths have dropped over time, driving some of the efficiency improvements characteristic of U.S. domestic production over the past decade.

The Bakken play has consistently had the lowest average drilling and completion costs of the basins and plays reviewed in the IHS report. Improvement in drilling rig efficiency and completion crew capacity helped drive down drilling costs per total depth and completion costs per lateral foot, since 2012. Recent declines are partly a result of an oversupply of rigs and service providers. Standardization of drilling and completion techniques will continue to push costs down.

Figure 4. Cost per vertical depth and horizontal length



Note: Midland and Delaware are two plays within the Permian basin, located in Texas and New Mexico

Source: IHS *Oil and Gas Upstream Cost Study commissioned by EIA*

Offshore costs

There are fewer than 100 deepwater wells in the Gulf of Mexico. Unlike onshore shale and tight wells that tend to be similar in the same play or basin, each offshore project has a unique design and cost profile. Deepwater development generally occurs in the form of expensive, high-risk, long-duration projects that are less sensitive to short-term fluctuations in oil prices than onshore development of shale gas and tight oil resources. Nevertheless, recent low commodity prices do appear to have reduced some Gulf of Mexico offshore drilling.

Key cost drivers for offshore drilling include water depth, well depth, reservoir pressure and temperature, field size, and distance from shore. Drilling itself is a much larger share of total well costs in offshore development than in onshore development, where tangible and intangible drilling costs typically represent only about 30% to 40% of total well costs.

According to the IHS report’s modeling of current deepwater Gulf of Mexico projects, full cycle economics result in breakeven prices that are typically higher than $60/b. Low oil prices force companies to control costs, increase efficiencies, and access improved technologies to improve the economics in the larger plays. Efforts are underway to renegotiate contract rates and leverage existing production infrastructure to develop resources with subsea tiebacks. Consequently, the IHS report forecasts a 15% reduction in deepwater costs in 2015, with a 3% per annum cost growth from 2016 to 2020. The large cost reduction in 2015 is most notable in rig rates because of overbuilding.

Exhibit 34.06

This exhibit was not previously submitted in November 2023

A Simple Model for Pricing and Trading Produced Water in the Permian Basin

Gabriel Collins, "A Simple Model for Pricing and Trading Produced Water in the Permian Basin," Texas Water Intelligence™, Water Note #3, 17 August 2016.

Selling produced water can significantly reduce operational costs, make US shale production more competitive, and bolster the industry's social license to operate.

Executive Summary

- Political pressure, legal changes, evolving frac designs, and the proliferation of large-scale produced water gathering, treatment, and recycling systems may help catalyze the development of a market for produced water in the Permian Basin. This analysis focuses on the Texas side of the Permian due to the more streamlined regulatory system and recognition of private ownership rights in groundwater and produced water in the Lone Star State.

- Produced water handling and disposal costs significantly affect OPEX, profitability, and overall economic competitiveness. Thus, there are strong incentives to flip produced water from a cost-center into a saleable, revenue-generating commodity, or at least make it cost-neutral on E&P balance sheets.

- Produced water treated at industrial scale could be supplied by pipeline or layflat hose to frac ponds within 10 miles of the recycling center at an "all-in" delivered price competitive with high-volume non-trucked freshwater, brackish water, and municipal effluent.

- A simple "back of the napkin" analysis assuming an initial infrastructure capital investment of $35 million, an avoided disposal cost of $0.50/bbl of water, and an incoming volume of 100 kbd of water suggests infrastructure costs could be paid back in 5-to-6 years for well-utilized facilities able to sell water at an "after cost" margin of $0.10 to $0.25/bbl.

- Producers' desire to avoid the legal liabilities that may be incurred from spills of highly saline water creates a logical business space for a water-oriented midstream operator. These firms' business models generally already fundamentally contemplates assuming the risk of owning and transporting saline water.

- As recycling and resale via industrial-scale systems with third party access become more cost-effective than investing in proprietary disposal and/or recycling loops, the Permian Basin produced water market could take off rapidly and transform operational cost structures.

- Significant produced water handling infrastructure capacity is already in place in various parts of the Texas Permian Basin. What is needed next is a paradigm shift that makes more operators begin to see produced water as a potential marketable asset outside their own proprietary systems.

Intro

Oilfield produced water is an abundant resource in Texas, with a minimum estimated volume of 20 million barrels produced each day (actual production may now exceed 25 million bpd). This is roughly equal to the combined net water use of Austin, Dallas, El Paso, Fort Worth, Houston, and San Antonio combined in 2014.

Yet E&Ps have historically viewed produced water largely as a commercial and legal liability that must be offloaded in order to enable oil production. Indeed, even in the present oil price downturn, producers continue to cite reducing water disposal costs as one of the steps they are undertaking to reduce production costs and stay competitive.

Produced water handling and disposal costs significantly affect OPEX, profitability, and overall economic competitiveness. Thus, there are strong incentives to flip produced water from a cost-center into a saleable, revenue-generating commodity, or at least make it cost-neutral on E&P balance sheets.

Logistical challenges remain but the confluence of five key factors strongly suggests that it now time to ask not what produced water costs, but rather, what is it worth? With its relatively friendly legal regime on oilfield fluids recycling and title transfer, Texas is a favorable location to explore the concept and with its globally-significant activity level, the Permian Basin is the ideal play to focus on first.

Key factors that could drive a produced water paradigm shift:

1. Increasing political pressure to minimize the use of fresh water for fracs;

2. Advancing water treatment technology;
3. A more permissible legal and regulatory environment;
4. Industry is favoring slickwater frac designs that are less sensitive to water salinity as well as developing frac chemistries that mitigate the effects of formerly troublesome ions found in many produced waters; and
5. The proliferation of industrial-scale water handling infrastructure in the Permian and Delaware Basins, including networks with two key characteristics: (A) water handling system-wide capacities that could feasibly be scaled up to a million bpd and (B) system owners who suggest they are willing to consider allowing third-party access to their systems.

Potential Pricing Models: Cost-Based and Variable, With Immense Space for Innovation and Creative Allocation of Risk

The produced water sales discussion centers on two interrelated pricing models: cost-based and variable (i.e. dynamic) pricing. In simplest terms, cost-based pricing presumes a party selling produced water would not want to sell it at a price less than what it costs to gather the water, treat it to a frac-usable standard, and then transport it to an end-user's pond.

The analysis here assumes sale to a third-party, with a 10% profit margin built into the final delivered price of the treated produced water. If the operations are instead handled by a dedicated midstream operator–an evolution the author believes is likely–the desired profit margin would likely rise, but could be offset by greater economies of scale.

The author acknowledges that for high-volume users who seek to procure longer-term water supply agreements, parts of the cost chain could vary. For instance, a user located near the treatment facility could obtain water via a short distance, high volume layflat hose. Such a purchaser could also seek volume discounts or consider purchasing dedicated capacity in the facility in exchange for a discount in the price of water supplied to it. Many deal permutations will likely arise if and when the trade develops.

Exhibit 1: Cost-Based Price of Produced Water versus Alternative Supply Options

USD/bbl

Source	Purchase Cost, $/bbl	Distance from source to frac pond, Mi	Transport Cost, pipeline	Transport cost, layflat	Transport cost, trucked	Estimated total cost delivered into pit, $/bbl
Freshwater, Dedicated Well on Tract	$0.40	2	–	$0.06	–	$0.46
Santa Rosa Brackish	$0.35-0.45	10	$0.16	$0.06	–	$0.57-0.67
Large-Scale Treated Produced Water, base	–	10	–	–	–	$0.67
High Volume Freshwater, layflat	$0.45	10	–	$0.30	–	$0.75
Large-Scale Treated Produced Water, high	–	10	–	–	–	$0.76
Odessa Muni Effluent	$0.27	25	$0.40	$0.15	–	$0.82
Freshwater, trucked	$0.50	10	–	n/a	$0.90	$1.40
Medium-Scale Treated Produced Water, base	–	10	–	–	–	$1.88
Medium-Scale Treated Produced Water, high	–	10	–	–	–	$1.97

Exhibit 2 (below) lays out the assumptions made in the produced water cost calculations, as well as their sources. The bottom line is that the biggest portion of the produced water's cost is the treatment phase. Preliminary data suggest that a combination of infrastructure scale, along with inbound water quality, exert particular influence on treatment costs per barrel. For instance, as of 21 June 2016, Approach Resources reported a treatment cost of $1.50/barrel for produced water handled in its 329,000 barrel Pangaea treatment center. In contrast, Apache has reported a treatment cost of only $0.29/barrel in its Barnhart recycling system, which has a 1.5 million barrel capacity.

As Exhibit 1 shows, produced water treated at a cost closer to the Apache figure likely means that recycled produced water could be supplied by pipeline or layflat hose to locations within 10 miles of the recycling center at an "all-in" delivered price competitive with high-volume non-trucked freshwater, brackish water, and municipal effluent. Please note that this model credits the skim revenue against other treatment costs, so water with lower recoverable hydrocarbon content will have a less favorable cost structure.

Exhibit 2: Produced Water Sale Cost Model

Assumptions	Cost	Units	Source
Gathering System Transport Cost	$0.02	per bbl per mile	Wolfcamp Water Partners, Discussions with 2 large layflat services vendors operating in Eagle Ford and Permian
Gathering System Transport Journey Length for a given barrel of water	7.5	miles	
Treatment Cost, Baseline (329kb capacity facility)	$1.50	per bbl	Approach Resources, June 2016 Investor Presentation
Treatment Cost, Low (1,500kb capacity facility)	$0.29	per bbl	Oil & Gas Journal (Apache Barnhart system)
Skim Revenue	$0.20	per bbl	NGL Partners, LP 2015 10-K report
Layflat transport cost, 5-mile (high)	$0.03	per bbl per mile	Discussions with 2 large layflat services vendors operating in Eagle Ford and Permian
Layflat transport cost, 5-mile (base)	$0.03	per bbl per mile	“”
Layflat transport cost, 10-mile (high)	$0.03	per bbl per mile	“”
Layflat transport cost, 10-mile (base)	$0.02	per bbl per mile	“”
Desired Profit Margin	10%		
Low Industrial Scale		Full Industrial Scale	
Cost-Based Price, 5-Mile Radius (base)	$1.76	Cost-Based Price, 5-Mile Radius (base)	$0.55
Cost-Based Price, 5-Mile Radius (high)	$1.80	Cost-Based Price, 5-Mile Radius (high)	$0.59
Cost-Based Price, 10-Mile Radius (base)	$1.88	Cost-Based Price, 10-Mile Radius (base)	$0.67
Cost-Based Price, 10-Mile Radius (high)	$1.97	Cost-Based Price, 10-Mile Radius (high)	$0.76

Variable pricing entails creating a more dynamic system that moves in response to real-time supply and demand forces. Generally, the cost-based price of the produced water would set the floor, but prices could rise significantly beyond this level if demand warranted. The all-in delivered cost of rapid response marginal supplies such as trucked freshwater would likely establish the upper bound for how high prices might go in a variably priced tight market situation.

Two core challenges would need to be overcome for variable pricing of produced water sales to function in practice. First, operators and service companies will need to share much more significant amounts of real-time data on water supply and demand in areas with infrastructure capable of redirecting water flows to meet evolving needs. Second, produced water gathering, treatment, delivery, and disposal infrastructure will need to be more tightly integrated to reduce the cost and time of water movement and maximize potential arbitrage opportunities.

Inelastic supply and demand pose surmountable challenges

Produced water systems are relatively demand-inelastic on the gathering system side. An operator is almost certainly not going to choke back an oil or gas well or open it up wider if demand for produced water rises because the well's primary purpose is to produce hydrocarbons, with the produced water being a byproduct commodity.

Frac water demand, on the other hand, is lumpy," with slow periods punctuated by spurts of intense demand as operators fill frac ponds. Treatment time and most importantly, storage capacity for treated produced water that is ready to sell, will dictate how responsive a system is to frac demand. A recent published SPE paper showed that Apache's pilot field plant for treating and reusing produced water in the Barnhart area of Irion County, Texas featured a residence time of 60-100 minutes in each of the system's four holding and treatment tanks. On this basis, it is reasonable to assume that a given barrel of water put into a chlorine dioxide-based treatment system would have a residence time of at least 5-6 hours.

Large volumes of treated water stored in tanks or a pond would offer a faster response time, albeit at the cost of building and maintaining the storage structure. Our conversations with field sources suggest that a 500kb lined impoundment costs roughly $500-600k to construct in many parts of the Permian Basin, with a lined million barrel pond likely to cost closer to $1.5 million. Once a lined impoundment is built–and covered to reduce costs imposed by evaporation losses–maintenance costs are generally low per unit of water stored. Such impoundments also offer the owner the option of integrating additional non-traditional water supplies such as Santa Rosa brackish water and municipal effluent into the treated produced water stream.

Blending also helps ensure a consistent quality water stream, since the chemical composition of incoming produced water streams may vary significantly well-by-well. Large operators are already doing this in their proprietary loops. For instance, Pioneer Natural Resources blends its recycled produced water in the Midland Basin with treated municipal effluent purchased from the City of Odessa, while Apache blends treated produced water with Santa Rosa brackish water in its Barnhart system in Irion

County. To that end, Apache reports that in 2013 in Irion County, it used 10 million barrels of brackish groundwater blended with 3.1 million barrels of treated produced water.

Operators could also blend freshwater volumes with produced water to yield an acceptable frac fluid. Blending decisions would likely be taken at the operator level on a well-by-well basis that took into account factors including, but not limited to: formation characteristics, frac chemistry constraints, what sources of water are timely available and in what quantities, and what their respective costs/prices are.

Payout for gathering, treatment, storage, and distribution assets is likely to be reasonably rapid in active areas, since the all in cost of produced water disposal via deep injection is likely to be at least $1.00 per barrel even in SWD facilities with pipeline access (at least $0.50/bbl in injection fees, closer to $0.75-0.85/bbl in many cases, plus pipeline transport costs). A simple "back of the napkin" analysis assuming an initial gathering/treatment/distribution infrastructure capital investment of $35 million, an avoided disposal cost of $0.50/bbl, and an incoming volume of 100 kbd of water suggests the following payback times:

Scenario A: Provision of treated water at the cost of gathering, treatment, and delivery, with no added profit margin. Payback in Year 7 at 75% utilization and Year 9 at 50% utilization.

Scenario B: Sale of Treated water at a profit margin of $0.05/bbl above cost. Payback in Year 6 at 75% utilization and Year 8 at 50% utilization.

Scenario C: Sale of Treated water at a profit margin of $0.10/bbl above cost. Payback in Year 6 at 75% utilization and Year 8 at 50% utilization.

What if produced water demand drops off...

Connectivity to disposal assets helps mitigate risks caused by sudden drops in demand for treated produced water. Basically, if demand drops off and the treatment plants slows runs, excess incoming water can be re-routed to the disposal wells and injected.

One key challenge here is that while having a pipeline with spare capacity to access disposal wells is in the produced water recycler's interest, it is not in the interest of an SWD operator to have idle capacity in his lines. One possible solution would be for the produced water recycler to pay the SWD operator for dedicated capacity. Another would be to create a traded capacity market where space on the inbound SWD line goes to the highest bidder. Another is for the recycler to construct sufficient captive SWD capacity to dispose of excess water during down periods–much as a refiner or gas processor maintains flare stacks to dispose of product during operational disruptions.

The most expensive water...

Once a frac is underway, water demand also becomes extremely unresponsive to price changes. The reason is simple–when the pit is filling up and the service provider is spooling up his pumps, the most expensive water is that which never makes it to the pit. In most cases, an operator would rather pay $5.00/bbl to get the pit topped off and the job pumped right than to insist on paying $0.50/bbl for water that never shows up. High-reliability and predictable produced water sources would help diversify supplies and alleviate these risks.

Likely Future Directions

If produced water becomes a saleable commodity, this will likely help catalyze the development of a more interconnected oilfield water infrastructure in the Permian Basin. One key issue is the heightened liability risk incurred by moving high-salinity produced water in pipelines, since pipeline ruptures tend to cause large spills.

Producers are likely to have varying risk appetites for moving saline water into large-scale treatment facilities and then re-distributing it out to frac ponds via pipeline, layflat hose, and in some cases, trucks. This creates a logical business space for a water-oriented midstream operator, whose business model generally already contemplates the risk of owning and transporting saline water.

It is likely that many operators in Texas will welcome the opportunity to transfer ownership of produced water to a midstream provider as rapidly as possible. Under Section 122 of the Texas Natural Resources Code, once the produced water is transferred with the intent that the midstream provider will treat it and send it to another party for drilling for, or production of, oil and gas, the original producer will generally no longer face tort liability for injuries caused by the produced water.

The "Holy Grail" is a large-volume open access produced water gathering and recycling system with significant geographical coverage that can also integrate other alternative water sources such as brackish water and municipal effluent. Sufficiently large and connected infrastructure can serve as a "magnet" for produced water from a range of operators by creating the ability to sell what was formerly an expensive waste product. As recycling and re-sale via industrial-scale systems with third party access become more cost-effective than investing in proprietary disposal and/or recycling loops, the Permian Basin produced market could take off rapidly and transform operational cost structures.

For operators and parties considering the sale or purchase of produced water, please contact us at gabe@texaswaterintelligence.com.

Exhibit 38.01

This exhibit was not previously submitted in November 2023

Environmental Science & Technology

Policy Analysis

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Assessing Human Health $PM_{2.5}$ and Ozone Impacts from U.S. Oil and Natural Gas Sector Emissions in 2025

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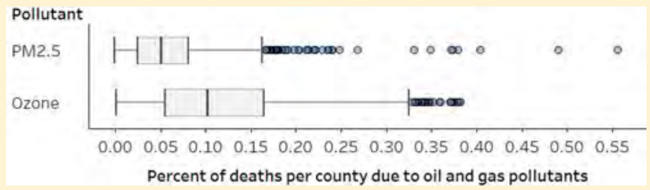
Supporting Information

ABSTRACT: Incomplete information regarding emissions from oil and natural gas production has historically made it challenging to characterize the air quality or air pollution-related health impacts for this sector in the United States. Using an emissions inventory for the oil and natural gas sector that reflects information regarding the level and distribution of $PM_{2.5}$ and ozone precursor emissions, we simulate annual mean $PM_{2.5}$ and summer season average daily 8 h maximum ozone concentrations with the Comprehensive Air-Quality Model with extensions (CAMx). We quantify the incidence and economic value of $PM_{2.5}$ and ozone health related effects using the environmental Benefits Mapping and Analysis Program (BenMAP). We find that ambient concentrations of $PM_{2.5}$ and ozone, and associated health impacts, are highest in a handful of states including Colorado, Pennsylvania, Texas and West Virginia. On a per-ton basis, the benefits of reducing $PM_{2.5}$ precursor emissions from this sector vary by pollutant species, and range from between \$6,300 and \$320,000, while the value of reducing ozone precursors ranges from \$500 to \$8,200 in the year 2025 (2015\$).



INTRODUCTION

Air pollution health burden assessments often characterize the ambient levels of pollution and enumerate the adverse health outcomes associated with emissions from total anthropogenic sources or certain classes of industrial and mobile sectors.[1−4] Studies quantifying the economic value of these impacts have also reported estimates of the monetized benefits of reducing emissions that are precursors to fine particles (particulate matter sized 2.5 μm and smaller, that is, $PM_{2.5}$) from a given sector; these are often referred to as a "benefit per-ton."[5−7] This literature provides insight regarding the size, distribution, and economic value of the air pollution impacts associated with emissions from a broad array of industrial activities including industrial boilers, cement kilns and refineries among other sectors.[8]

While there is a growing literature examining air quality and human health impacts attributable to the oil and natural gas sector in the United States, we were unable to identify any studies employing a national emissions inventory coupled with a photochemical grid model to simulate the nonlinear formation of pollutants including ozone and $PM_{2.5}$ attributable to this sector.[9] Some studies have assessed the risks attributable to this sector within discrete geographic areas and employed less computationally complex air quality modeling approaches to monetize health impacts from oil and natural gas production nationwide.[10,11]

This work has been encumbered in part by limited data regarding the level and geographic distribution of emissions associated with oil and natural gas production across the U.S. As we describe below, emissions from this sector tend to originate from a large number of small but geographically diffuse sources located throughout several basins, making it challenging to estimate both the level and location of emissions accurately. These uncertainties, in turn, have made it difficult to simulate $PM_{2.5}$ and ozone air quality with confidence. In this paper, we apply an emissions inventory for the oil and natural gas sector that reflects a spatially detailed nationwide estimate of the level and distribution of emissions from this sector. This version of the U.S. Environmental Protection Agency's (EPA) National Emissions Inventory (NEI) for the year 2011 includes data that States provided as part of the process for developing the NEI; these data substantially improve our ability to characterize oil and natural gas emissions over space and time as compared to previous versions of the emissions inventory for these sources.

This improved inventory permits us to simulate of air quality impacts from this sector's emissions, with the goal of answering three key questions:

- What are the annual average $PM_{2.5}$ concentrations and summer season average daily 8-h maximum ozone concentrations associated with this sector?
- What is the human health burden—in terms of $PM_{2.5}$ and ozone-related premature deaths and illnesses—

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Table 1. Emission Levels for the Oil and Natural Gas and All Other Sectors in 2025 (tons/year)

	pollutant					
	NO_x	SO_2	NH_3	CO	VOC	elemental and organic carbon
oil and gas	1 190 846	108 619	5927	978 765	3 671 787	10 451
biogenics	1 020 456			6 749 945	44 712 816	
fugitive dusts						51 370
residential wood combustion	34 805	7619	18 211	2 328 506	408 910	208 118
industrial point sources	1 021 969	783 630	66 612	1 884 412	786 950	69 062
electricity generating units	2 021 937	2 089 206	46 238	907 624	42 253	23 149
area sources	75 462	95 102	94 938	278	3 426 185	212 672
wildland fires[a]	333 404	165 790	329 398	20 566 821	4 689 022	1 075 975

[a]Assumed constant from the 2011 baseline.

attributable to the oil and natural gas sector and how is this burden distributed over the U.S?

- What are the health benefits—in terms of avoided deaths and illnesses—of reducing $PM_{2.5}$ and ozone precursor emissions on a per ton basis and how does the benefit per ton (BPT) vary across pollutant precursor?

Below we describe our approach to modeling emissions and air quality before detailing our methodology for estimating the incidence and economic value of air pollution-attributable premature deaths and illnesses and calculating BPT values. We then present the results of this analysis before discussing the implications of this research.

MATERIALS AND METHODS

Estimating Emissions. This analysis of the oil and natural gas sector draws upon estimates of pollutant emissions reported in the U.S. EPA NEI, which incorporates national activity, emission factors and basin-specific information submitted by State and Local agencies for this sector. Activity data are specific to each county for the year 2011. For the purposes of this analysis, we define the oil and natural gas sector as comprising an array of processes and equipment, including: drill rigs, workover rigs, well completions, well hydraulic fracturing, heaters, storage tanks, mud degassing, dehydration, pneumatics, well venting, fugitives, truck loading, wellhead engines, pipeline compressor engines, flaring, artificial lifts, and gas actuated pumps. These sources reflect the production and transportation of crude oil and natural gas and distribution of natural gas but exclude refineries and the distribution of refined products. The U.S. EPA defined the sector to reflect those activities covered by the New Source Performance Standards. Previous U.S. EPA analyses have assessed the air quality and health impacts associated with pollutants emitted during the refining process and so we exclude this sector here.[12]

Most oil and natural gas emissions data are estimated by county and spatially allocated to the model grid using surrogates that are based on year 2011 well locations and attributes related to the production of oil and natural gas and their byproducts. This procedure is described in the technical support document "Preparation of Emission Inventories for the Version 6.2, 2011 Emissions Modeling Platform"; the "platform" in this context describes the baseline inventory, meteorological model and air quality model used to simulate air quality.[13,14]

Beginning with this inventory, the U.S. EPA developed a method for estimating nonpoint emissions for the oil and natural gas production sector. In April of 2012, the Agency began collaborating with an extensive national workgroup comprised of state and regional emissions developers. This effort yielded a substantially improved Nonpoint Oil and Gas Emission Estimation Tool, which produces county-level emissions for calendar year 2011 for criteria pollutants and their precursors including volatile organic compounds and ammonia.[15] Both states and the U.S. EPA applied this tool to estimate emissions, either using the default tool inputs, or by providing their own basin- and/or county-specific inputs.

In brief, as part of a national outreach effort, U.S. EPA received data from two Regional Planning Organizations—the Lake Michigan Air Directors Consortium (representing Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin) and the Mid-Atlantic Regional Air Management Association (representing 10 state and local agencies including the Allegheny County Air Quality Program, the Pennsylvania Department of Environmental Protection, the North Carolina Department of Natural Resources, the Virginia Department of Environmental Quality and the West Virginia Department of Environmental Protection). In total, the states submitting data included CA, CT, DC, DE, IA, ME, MI, NC, NE, NY, PA, OK, TX, UT, VA, WA. Each organization provided information including the location, emission rate and controls. VOC and $PM_{2.5}$ emissions are speciated based on basin-specific speciation factors provided by the Western Regional Air Partnership.[13,14] National VOC and $PM_{2.5}$ speciation profiles were used for this assessment where location speciation profiles were unavailable. Annual total emissions for this sector are evenly distributed across each hour of each day using temporal allocation factors that account for units operating continuously throughout the year.

To account for the expected change in the size and distribution of this sector over time, we projected the 2011 sector emissions to the year 2025 using economic growth factors based on product and consumption indicators derived from the Annual Energy Outlook (AEO) 2014 (Table 1).[13,14] We selected a future year of 2025 because it was most relevant for U.S. EPA air quality planning purposes. The AEO projected growth rates for each U.S. Census Division, which were then assigned to each basin. Projected levels of emissions from the sector can be useful to policy makers as they seek to understand the future air quality and health impacts attributable to the sector. However, as we note below, this procedure also introduces uncertainty to the analysis. Aside from the growth factors, emission reductions are reflected for some oil and natural gas categories including reductions of criteria air pollutants due to stationary reciprocating internal combustion engine regulations that reduce emissions of hazardous air pollutants and New Source Performance

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Standards. Additional details regarding our approach are available in the Version 6.2, 2011 Emissions Modeling Platform TSD.

Air Quality Modeling Simulations. The Comprehensive Air-Quality Model with extensions (CAMx) version 6.20[16,17] was applied for the entire year of 2011 with a 10 day "spin-up" period at the end of 2010 to minimize the influence of initial conditions. The model domain covered the contiguous United States with 12 km by 12 km sized grid cells. The surface to model top (~15 km) was resolved with 25 layers with most in the boundary layer to best capture the diurnal variation in the surface mixing layer. CAMx has treatment of gas-phase chemistry based on Carbon Bond 6, inorganic particulate matter thermodynamics based on ISORROPIA, aqueous phase chemistry, and semivolatile partitioning of VOC to secondary organic aerosol.[16,18,19] In this assessment, CAMx was not modified to capture wintertime ozone formation that is associated with production activities in certain oil and natural gas basins, meaning the ozone air quality and health impacts provided here are entirely associated with traditional warm season (May 1 to September 30) ozone formation.[20,21] Moreover, the risk coefficients we used to quantify ozone effects were drawn from studies assessing the health risks associated with warm season ozone exposure; modeling ozone in this way ensures that the exposure estimates are consistent with the health impact assessment described below.

CAMx was applied with source apportionment to differentiate the contribution of the oil and natural gas sector from all other emissions. The contribution of oil and natural gas emissions was tracked to model estimated primary ($PM_{2.5}$ elemental carbon, $PM_{2.5}$ organic carbon, and crustal compounds) and secondary (e.g., ozone contributions from NO_x, ozone contributions from VOC, $PM_{2.5}$ sulfate ion, $PM_{2.5}$ nitrate ion, and $PM_{2.5}$ ammonium ion) pollutants.[16,22−24] The contribution of VOC emissions to secondary organic aerosol (SOA) were not tracked because the model estimates a very small amount of anthropogenic SOA (from all sources) and while this sector emits a large amount of VOC, the bulk of the species contributing to the emissions mass (e.g., methane, ethane, propane) are not known to yield large amounts of SOA. Year 2011 meteorological inputs were generated using the Weather Research and Forecasting model.[25] WRF was applied with a domain consistent with the photochemical grid model and has been shown to compare well with surface, upper air, and mixing layer height measurements.[26] Further details about the WRF configuration are provided in the Supporting Information. Initial chemical conditions and boundary inflow were extracted from a global model simulation using a database tool developed jointly by the University of Florida and the U.S. EPA, and subsequently translated to match the domain and chemical species employed for this assessment.[27] Both biogenic and anthropogenic emissions were incorporated into the air quality modeling. Biogenic emissions were estimated using the Biogenic Emission Inventory System version 3.6.1.[13,28,29] Anthropogenic emissions were based on the 2011 National Emission Inventory version 2 as described in the associated technical support document.[14,30] Wildland fire emissions were also included in the 2011 NEI version 2 and are based on known fires in 2011.[31]

Estimating Counts of Air Pollution-Related Deaths and Illnesses Attributable to the Oil and Natural Gas Sector. We calculate a health impact function to quantify counts of premature deaths and illnesses attributable to the model-predicted $PM_{2.5}$ and ozone from the oil and natural gas sector. For each $PM_{2.5}$ and ozone human health end point we calculate a separate health impact function. Each function specifies four input parameters: (1) an effect coefficient (or, beta parameter) from a published air pollution epidemiology study; (2) a count of the number of people affected in each 12 km by 12 km air quality grid from the U.S. census; (3) the air quality concentration to which the population is exposed from the photochemical model; (4) a baseline rate of death or disease among this population from Centers for Disease Control and Prevention and the Agency for Healthcare Research and Quality.

To automate the procedure for calculating health impacts we used the open-source environmental Benefits Mapping and Analysis Program—Community Edition software program.[32] The $PM_{2.5}$-related health outcomes we quantify include premature death, respiratory hospital admissions, cardiovascular hospital admissions, emergency department visits for asthma, upper respiratory symptoms, lower respiratory symptoms, days of work lost, days of school lost, cases of aggravated asthma, and cases of acute respiratory symptoms. We quantify ozone-related end points including premature death, respiratory hospital admissions, respiratory emergency department visits, exacerbated asthma, and days of school missed.

Using the health impact function for $PM_{2.5}$-related deaths as an example, we specify the input parameters below. In eq 1, we estimated the number of $PM_{2.5}$-related total deaths (y_{ij}) for adults in each county j ($j = 1,\cdots,J$ where J is the total number of counties) as

$$y_j = \Sigma_a y_{ja}$$

$$y_{ija} = m0_{ja} \times (e^{\beta \cdot C_k} - 1) \times P_{ika}, \qquad (1)$$

where β is a beta coefficient for all-cause mortality in adults associated with annual average exposure to $PM_{2.5}$, $m0_{ja}$ is the baseline all-cause death rate for adults in county j stratified in 10-year age bins, C_k is the annual mean $PM_{2.5}$ concentration in air quality grid cell k, and P_{ka} is the number of adult residents in air quality grid cell k stratified into 5-year age bins. The program assigns the all-cause death rates for adults in county j to grid cell k using an area-weighting algorithm described in the BenMAP-CE user manual.[33] This health impact function returns a count of the number of $PM_{2.5}$-related deaths occurring in each county due to annual mean $PM_{2.5}$ concentrations. The function above can be generalized to the remaining $PM_{2.5}$ morbidity and ozone mortality and morbidity end points; when quantifying ozone-attributable premature deaths, we substituted a daily average mortality rate for the annual mortality rate noted above.

Our approach for specifying the health impact functions above is consistent with the methodology the U.S. EPA employed in the Regulatory Impact Analyses (RIAs) supporting the $PM_{2.5}$ and Ozone National Ambient Air Quality Standards (NAAQS).[34,35] These two RIAs considered evidence the Agency evaluated in the Integrated Science Assessments (ISAs) for Particulate Matter and Ozone. The ISAs systematically reviews the toxicological, epidemiological, and clinical evidence for each pollutant, carefully assessing the evidence before determining whether each pollutant is causally associated with a given health outcome. After identifying the

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human health end points as being either causally, or likely to be causally, associated with each pollutant, the RIA next evaluates the epidemiological studies quantifying these end points. As noted in the PM NAAQS RIA, the Agency "··· follow[s] a weight of evidence approach, based on the biological plausibility of effects, availability of concentration-response functions from well conducted peer-reviewed studies, cohesiveness of results across studies, and a focus on end points reflecting public health impacts···rather than physiological responses."[34] That RIA further specifies a host of criteria the Agency considers when selecting effect coefficients, including the study type, population attributes, pollutant measures, and other attributes.

To quantify PM-related premature deaths, we derived a long-term mortality β coefficient from a Hazard Ratio reported in the most recent extended analysis of the American Cancer Society (ACS) cohort (ages 30 and older) (β = 0.0058; SE = 0.000962) (Supporting Information Table S-1).[36] To estimate ozone-related premature deaths, we derive a short-term mortality β coefficient from an estimate of the percentage increase in the risk of ozone-related death from a multicity analysis (ages 0−99) (β = 0.00051; SE = 0.00012) (Supporting Information Table S-2).[37]

As noted below, the dollar value associated with the incidence of air pollution-related deaths is considerable, and so we searched the literature to identify alternative concentration−response parameters from more recently published epidemiological studies. We were unable to identify a long-term epidemiological study of $PM_{2.5}$ all-cause mortality for a representative U.S. cohort of both adult males and females that was more current than Krewski et al. (2009) .[36] However, as a sensitivity analysis, we also quantify risks using the hazard ratio from the extended analysis of the Harvard Six Cities study Lepuele et al. (2012); these results may be found in the Supporting Information (Table S-6).[38] We found that the Zanobetti & Schwartz (2008) ozone multicity study exhibited a number of strengths, including its evaluation of multiple exposure lags and its pooling of the single-city risk coefficients to derive a single national risk coefficient.[39] As a sensitivity analysis, we also report ozone-attributable premature deaths using the results of other broadly cited ozone mortality studies, including a multicity study (Table S-6).[40]

We performed a Monte Carlo-based simulation to construct an error distribution of estimated $PM_{2.5}$ and ozone-related effects. To inform the Monte Carlo simulation, we constructed a distribution around each effect (or, beta) coefficient using the standard error reported in each study; these resulting distributions are normally distributed (Table S-1). We calculated total numbers of premature deaths and illnesses in the contiguous U.S. for each year by summing the county-specific estimates, and report the sums of the 2.5th and 97.5th percentiles of the Monte Carlo distributions as 95% confidence intervals. As we note below, this distribution became an input to the Monte Carlo simulation we performed when quantifying a distribution of economic values. We use information regarding the distribution around each of the other input parameters (i.e., air quality, baseline incidence and population) and thus treated these parameters deterministically.

We defined m_{0ja} as the county-level age-stratified all-cause death rates from the Centers for Disease Control Wide-ranging Online Data for Epidemiologic Research database.[41] To account for the improved longevity of the population over time, we projected these death rates to future years using a life table reported by the U.S. Census Bureau (Supporting Information Tables S-3 and S-4). We defined the baseline incidence rates for the morbidity end points using rates of hospital admissions, emergency department visits and other outcomes for the year 2014 from the Healthcare Cost and Utilization Program (Supporting Information Table S-5). We defined P_{ka} using age-stratified population data from the U.S. Census Bureau. We projected population to year 2025 using an economic and demographic forecast from the Woods & Poole company.[42]

We calculated the fraction of all deaths due to $PM_{2.5}$ and ozone in each county and year using the following function:

$$AF_j = \frac{y_j}{\Sigma_a m0_{ja} \times P_{ja}} \tag{2}$$

where y_j is the estimated number of air pollution deaths, $m0_{ja}$ is the age-stratified baseline death rate, and, P_{ja} is the age-stratified population, respectively, in county j.

We calculated the population-weighted annual mean concentration for all counties combined (C) as

$$C = \frac{\sum_j C_j \times P_j}{P} \tag{3}$$

where C_j is the county-average $PM_{2.5}$ concentrations in county j, P_j is the population in county j, and P is the total population over all counties combined.

Estimating Economic Values of Air Pollution Effects. We estimate the economic value of the $PM_{2.5}$ and ozone-attributable premature deaths and illnesses on a per-ton of emissions basis using an approach that is consistent with the approaches used in the U.S. EPA's Ozone and PM NAAQS RIAs.[34] Those analyses applied a suite of willingness to pay (WTP) and cost of illness (COI) unit values built into the BenMAP-CE software that relate counts of adverse health outcomes to an estimated dollar value. A WTP measure describes the value that society places on avoiding some adverse health outcome. By contrast, COI reflects the direct costs associated with an adverse event; this can include medical expenses associated with a hospital visit and the value of lost productivity.

Because the value associated with air pollution-related premature deaths tends to account for as much as 99% of the total dollar value of a given air pollution health benefits assessment, it is worth detailing our method for valuing this end point. We apply a value of statistical life (VSL) to estimate the value of air pollution-related deaths. The VSL reflects the amount of money that a large number of people are willing to pay to reduce their risk of death by a small amount. As an example, 10 000 people might be willing to pay $500 to reduce their risk of death by 1-in-10 000; this yields a VSL of $5M. In this analysis, we apply a base VSL of $6.3 M in year 2000$ that is constant for all adult populations. This value is derived from a meta-analysis of 26 value of life studies published over a two-decade period.[43] While the number of publications reporting VSLs in the U.S. is quite large, we selected a value from this study because it has been applied extensively in the literature, making it easier to compare values in this manuscript to those published elsewhere.[2,6,44] The uncertainty around this mean value is represented by a Weibull distribution. We adjust this value in two ways. First, we inflate the VSL to year 2015$. Next, we account for the role of income growth in increasing future willingness to pay to reduce the risk of death by

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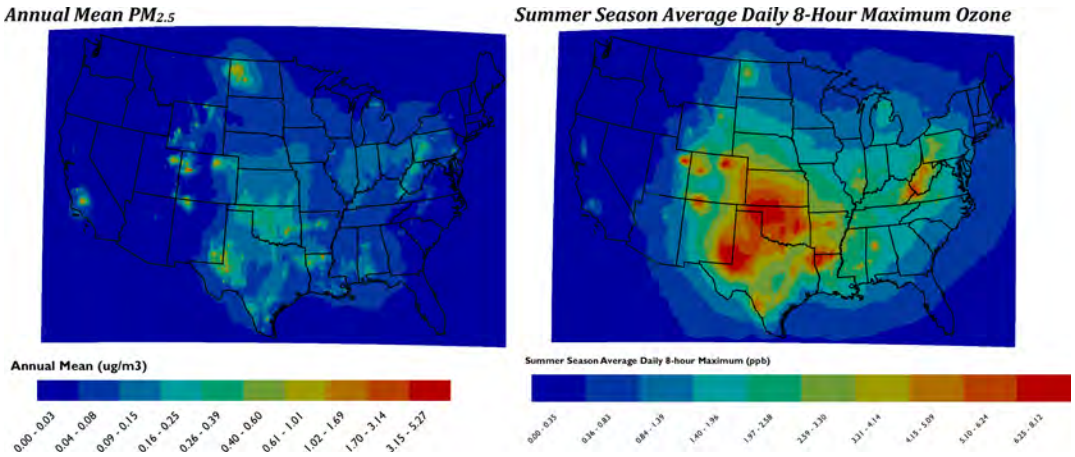

Figure 1. Annual Mean $PM_{2.5}$ and Summer Season Daily 8 h Maximum Ozone Attributable to the Oil and Natural Gas Sector in 2025. State and county boundaries drawn according to Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line files in the ArcGIS software.

Table 2. Distribution of CAMx Model Predicted Annual Mean $PM_{2.5}$ and Summer Season 8-h Maximum Ozone Concentrations and Population-Weighted Levels for the Oil and Natural Gas Sector in 2025[a]

		percentile								
pollutant	min	10%	25%	50%	75%	90%	max	mean	SD	national population-weighted value
$PM_{2.5}$ (ug/m^3)	<0.01	0.0034	0.009	0.02	0.06	0.1	5.27	0.04	0.07	0.0557
SO_4	<0.01	0.001	0.004	0.008	0.016	0.03	0.55	0.013	0.015	0.02
NO_3	<0.01	<0.01	<0.01	<0.01	0.01	0.04	0.25	0.01	0.2	0.02
directly emitted $PM_{2.5}$	<0.01	<0.01	<0.01	<0.01	0.01	0.01	2	<0.01	0.02	<0.01
ozone (ppb)	<0.01	0.068	0.19	0.57	1.59	2.91	8.12	1.12	1.36	1.34
NO_x	<0.01	0.05	0.2	0.6	1.7	3	7.6	1.16	1.36	1.24
VOC	<0.01	<0.01	0.02	0.04	0.08	0.16	3.2	0.07	0.09	0.1

[a]Calculated from 12 × 12 km model predicted concentrations.

projecting the VSL to the year 2025. Adjusting the base VSL for these two factors yields a VSL of \$10.4 M for the year 2025 in 2015\$.

Benefit Per-Ton Calculation. We calculated the dollar per-ton for the contiguous United States BPT_i as

$$BPT_p = \frac{\sum_{bp}}{\text{emissions}_p} \tag{4}$$

where BPT_p is the dollar benefit per ton for a given $PM_{2.5}$ or ozone precursor, b is the total dollar benefits summed across all health end points for precursor p and emissions_p is the national sum of emissions for precursor p.

■ RESULTS

The CAMx model predicted annual mean $PM_{2.5}$ concentrations attributable to the sector ranging from a maximum of 5.27 μg/m^3 (located in western Colorado) to less than 0.001 μg/m3, with a median value of 0.04 μg/m^3 (Figure 1 and Table 2). States including Illinois, Ohio, and Pennsylvania in the east; Alabama, Louisiana, Oklahoma, and Texas in the south; North Dakota in the midwest; and Colorado and Wyoming in the west, experience the greatest $PM_{2.5}$ concentrations from the oil and natural sector (Figure 1). The predicted summer season average 8-h maximum ozone value ranges from a high of 8.12 ppb (located in Western Texas) to a low of 0.003 ppb, with a median value of 0.57 ppb (Figure 1 and Table 2). West Virginia in the east and Alabama, Louisiana, Nebraska, Oklahoma, and Texas in the south experience the greatest summer season ozone levels from this sector (Figure 1). The national population-weighted annual mean $PM_{2.5}$ value is about 0.05 μg/m^3 while the population-weighted summer season average 8 h maximum ozone value is 1.34 ppb (Table 2).

For the year 2025, we estimate 970 (95% confidence interval 670−1300) ozone-related premature deaths and 1000 (95% confidence interval 520−1400) $PM_{2.5}$-related deaths nationwide (Table 2). We also estimate about 1000 respiratory and cardiovascular hospital admissions, 3600 emergency department visits, tens of thousands of upper and lower respiratory symptoms, approximately 100 000 lost work days, and over a million cases of exacerbated asthma and acute respiratory symptoms (Table S-6). Because the air quality impacts from this sector are spatially heterogeneous, we also report state-by-state estimates of PM and ozone-related premature deaths. The PM and ozone-related mortality burden is the in Texas, Pennsylvania, Ohio, Oklahoma, Illinois, California, Michigan, Colorado, Indiana, and Louisiana (Table 3). To account for the role of population size in influencing these values, we also report the number of PM and ozone-related deaths per 100 000 people, finding that Oklahoma, Louisiana, Colorado, Pennsylvania and Indiana experience the largest number of deaths on a population-normalized basis (Figure 2). Estimated dollar values for these cases of premature death range from \$13 to \$28 billion and cases of illnesses range from \$1 to \$200 million depending on the end point; full results may be found in Supporting Information Table S-7.

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Table 3. National-Total and Selected State $PM_{2.5}$-and Ozone-Related Premature Deaths Attributable to Emissions from the Oil and Natural Gas Sector in 2025

	estimated numbers of premature deaths (95% confidence interval)[b]			
state[a]	attributable to $PM_{2.5}$	attributable to ozone	total deaths attributable to $PM_{2.5}$ and ozone	total deaths per 100 000 people
Texas	130 (88—170)	130 (70—190)	260 (160—370)	1.4
Pennsylvania	85 (57—110)	55 (30—80)	140 (87—190)	1.6
Ohio	65 (44—86)	48 (26—70)	110 (69—160)	1.5
Oklahoma	48 (32—63)	55 (29—81)	100 (62—140)	4.1
Illinois	55 (37—73)	38 (20—55)	92 (57—130)	1.1
California	59 (40—77)	14 (7.4—20)	72 (47—97)	0.27
Michigan	39 (26—52)	32 (17—47)	71 (44—98)	1.1
Colorado	37 (25—49)	34 (18—49)	70 (43—98)	1.9
Indiana	38 (26—50)	29 (15—42)	66 (41—92)	1.6
Louisiana	34 (23—45)	28 (15—40)	61 (38—85)	2
national total	1000 (670—1300)	970 (520—1400)	1900 (1100—2700)	0.9

[a]These states comprise the largest health impacts for the sector. States listed by descending order of total $PM_{2.5}$ and ozone-attributable deaths. [b]All values rounded to two significant figures.

We also estimate the national BPT values for PM and ozone precursors by dividing the total estimated benefits associated with each ozone precursor or PM species by the tons emitted of that precursor. Modeled precursors of PM elemental and primarily emitted organic carbon (EC/OC), SO_2, and oxides of nitrogen (NO_x), and NO_x and VOC precursors were modeled for ozone. For the purposes of estimating the incidence attributable to each PM species, we assume that each specie is as detrimental to health as total PM mass. The two largest BPT estimate ranges were for the PM precursors to EC/OC and sulfate, at \$140,000−\$320,000 and \$27,000−\$62,000, respectively (2015\$ for all estimates); this range reflects the sum of the value of the morbidity end points and the long-term PM mortality coefficients from Krewski et al. 2009 at the low end and Lepeule et al. 2012 at the high end. The BPT ranges for the PM precursor to nitrate and the ozone precursor NO_x were of similar magnitudes, at \$2,800−\$6,300 and \$4,600−\$8,200, respectively. The range of economic value per ton of ozone-related VOC from the oil and natural gas sector was \$300−\$500; this range reflects the sum of the value of morbidity impacts and the Smith et al. 2009 ozone mortality risk coefficient at the low end and the Zanobetti & Schwartz 2008 risk coefficient at the high end.

■ DISCUSSION

The oil and natural gas sector emits pollutants that contribute to forming ozone and fine particles in the atmosphere, degrading air quality and ultimately adversely affecting public health in the form of premature deaths, hospital admissions, emergency department visits, cases of aggravated asthma, and lost days of school and work, among other outcomes.

While we were unable to identify other national-scale estimates of the air pollution impacts for this sector in the literature, we can place the estimates above in the context of analyses assessing the overall burden of $PM_{2.5}$ and ozone on health. The Global Burden of Disease study estimates about 100 000 $PM_{2.5}$ and ozone-related deaths in the United States for the year 2016.[4] A separate analysis of the U.S. reported about 130 000 $PM_{2.5}$ and ozone-related deaths for the year 2005.[45] The total number of oil- and natural gas-attributable $PM_{2.5}$ and ozone premature deaths represents a small fraction of the national burden these two analyses estimates. Because both the national burden analyses retrospectively estimate $PM_{2.5}$ and ozone-attributable deaths for 2010 and 2005, it is difficult to compare directly against these 2025-projected estimates. Moreover, neither national burden analyses reported state-by-state estimates of air pollution burden, which would arguably be a more relevant geographic unit of comparison for this sector, given the spatially heterogeneous air quality impacts from oil and natural gas facilities.

The results above indicate that the air quality and health impact associated with this sector correspond closely with the location of oil and natural gas facilities. Six states—Texas, Oklahoma, Colorado, North Dakota, West Virginia, and Pennsylvania—contributed almost 70% of the onshore natural gas production and over 74% of the onshore crude oil production in the lower 48 states in 2016.[46,47] These states also experience the highest levels of ground-level ozone and fine particle levels attributable to this sector. While the modeled ambient levels of fine particles are more spatially heterogeneous, ozone concentrations appear to be more spatially homogeneous across states including Nebraska, Oklahoma and Texas, suggesting a role for interstate transport. The estimated premature ozone and $PM_{2.5}$-related mortality corresponds well with the location of the air quality impacts. Indeed, in the western U.S., the sector tends to contribute $PM_{2.5}$ among locations in which fine particle levels are projected to be quite low—generally below about 6 $\mu g/m^3$. While we expect these areas to experience projected $PM_{2.5}$ levels well below the annual NAAQS of 12 $\mu g/m^3$, we quantify cases of excess $PM_{2.5}$-related premature deaths and illnesses in these locations because evidence suggests that there is no population-level concentration threshold for fine particles.

To our knowledge, this manuscript is the first reported benefit per-ton estimates for precursor emissions to $PM_{2.5}$ or ozone for the oil and natural gas sector derived from full-form photochemical grid modeling.[10] The $PM_{2.5}$-related health benefits of direct PM, sulfur dioxide (SO_2), and NO_x have previously been characterized for emission reductions from 17 industrial, area, and mobile emission sectors in the U.S. for the

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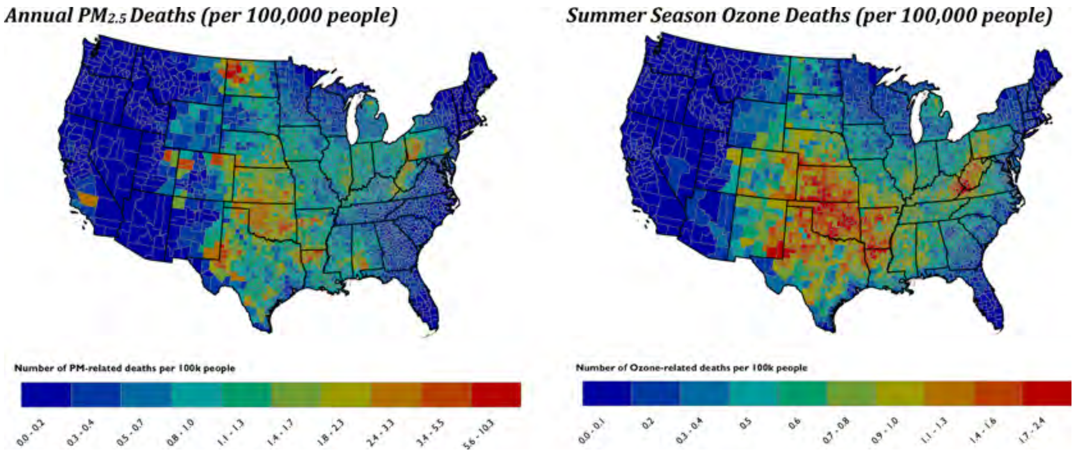

Figure 2. Premature Deaths (per 100 000 people) attributable to annual mean $PM_{2.5}$ and Summer season daily 8 h maximum ozone from the oil and natural gas sector in 2025. State and county boundaries drawn according to Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line files in the ArcGIS software.

year 2016.[48] That manuscript published in 2012 did not quantify impacts from the oil and natural gas sector because of uncertainties associated with the 2005 emissions inventory for that sector. Direct PM BPT estimates for these 17 sectors range from $45,000–$490,000, which is comparable with our EC/OC BPT estimate of $140,000–$320,000. Similarly, our sulfate and nitrate BPT values ($27,000–$62,000 and $2,800–$6,300, respectively) fell within the range of SO_2 and NO_x BPT estimates for the 17 sectors ($12,000–$97,000 [with one exception: $400,000 for the iron and steel sector] and $1800–$16,000, respectively). As the BPT estimates presented here are comparable with previously published BPT values, we believe them to be reasonable.

Among all species and precursors considered in this study, the lowest BPT estimates were for VOC contributions to ozone formation (fewer than 100 deaths in 2025) than for NO_x (over 900 deaths each in 2025). In addition, there were considerably fewer restricted activity days, the health outcome with the second highest value, associated with VOC (under 170 000) than with NO_x (over 2 million). Another reason for less impact from VOC compared to NO_x is that most source areas tend to be located in places that are VOC-rich (also referred to as NO_x-sensitive) meaning that additional VOC has less impact than NO_x. This heterogeneity in ozone formation regime is reflected in the contribution results which is a strength of using a photochemical model to support ozone impact assessments.

Loomis and colleagues apply a suite of benefit per-ton values reported in the literature to quantify the air pollution impacts attributable to hydraulic fracturing in 14 states.[5,7,8] The authors calculate an average of these values, weighted according to whether the wells are located in urban or rural locations. The authors estimate the economic value of emissions from hydraulic fracturing of between $14 and $48B (2015$). Litovitz and colleagues quantify the economic value of air pollution impacts shale gas production in Pennsylvania, by employing the Air Pollution Experiments and Policy Analysis (APEEP) model.[7,11] This study estimates total damages of between $7.2 M and $32 M for Pennsylvania. While the present analysis did not report the total national economic value for the sector, multiplying the BPT values reported above against the sector emissions yields an estimate of between $13B to $29B, which is comparable to the value reported by Loomis et al.

Analyses of this scope and complexity are subject to important uncertainties and limitations. First, quantifying the air quality and health impacts for this sector is especially challenging because of uncertainties in the emission inventory for oil and natural gas production and transmission. These uncertainties can vary from basin to basin meaning that impacts in some areas may be better characterized than others depending on the level of effort provided by state and local agencies toward generating emissions and activity data for their particular area. The projected level of oil and natural gas production in 2025 is also sensitive to the price of oil in that year, which we cannot account for completely in this analysis. Further, uncertainties in the assumed composition of VOC emissions can be important, especially if the currently assumed composition is biased low for highly reactive VOC meaning less potential to facilitate ozone formation. We modeled an emissions inventory that was the best available at the time of the analysis and itself represented substantial improvements over previous inventories. Another uncertainty associated with quantifying an ozone-related BPT value in particular is that ozone-related impacts are sensitive to baseline levels of VOC and NO_x. These levels differ by location and are not assumed to change over time as these baseline pollutant levels change. Similarly, $PM_{2.5}$ impacts are sensitive to baseline levels of ammonia and in the case of nitrate ion also to favorable weather conditions (e.g., cool temperatures and higher relative humidity). $PM_{2.5}$ impacts from this sector are likely under-represented to some degree since impacts on SOA were not quantified. VOC emissions from this sector (e.g., aromatics) are known to form SOA and the NO_x emissions in proximity to biogenic VOC may also contribution to SOA formation.[49,50]

To the extent that future populations are healthier and more resilient to air pollution than we have forecast in this analysis, and thus more resilient to air pollution, then the BPT values may be overstated. The Monte Carlo analysis described above accounts only for the statistical uncertainty associated with the pollutant effect coefficients and economic unit values; it does not account for a host of other uncertainties associated with the emissions inventory, air quality modeling, baseline health or demographic information. Finally, the estimates of economic value are sensitive to the VSL that we applied;

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using a different VSL might increase or decrease the values reported here.

These uncertainties notwithstanding, we believe the manuscript provides important insight to the heath burden associated with oil and natural gas production in the U.S. This manuscript is the first to estimate the benefits of reducing emissions from this sector on a per-ton basis using full-form modeling; these values may be useful to those evaluating air quality management policies affecting this sector.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b02050.

Additional details regarding: our approach for estimating population exposure and the health impact functions we applied(PDF)

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■ ABBREVIATIONS

BenMAP environmental Benefits Mapping and Analysis Program
CAMx Comprehensive Air Quality Model with extensions
EPA Environmental Protection Agency
ICD International Classification of Disease
MATS Mercury and Air Toxics Standards
NAAQS National Ambient Air Quality Standards
O_3 Ground-level ozone
$PM_{2.5}$ Particulate matter, 2.5 μm or less in diameter
RRF Relative Response Factor
WHO World Health Organization

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Exhibit 38.02

This exhibit was not previously submitted in November 2023

Environmental Science & Technology

Critical Review

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Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development

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ABSTRACT: The rapid increase in unconventional natural gas (UNG) development in the United States during the past decade has brought wells and related infrastructure closer to population centers. This review evaluates risks to public health from chemical and nonchemical stressors associated with UNG, describes likely exposure pathways and potential health effects, and identifies major uncertainties to address with future research. The most important occupational stressors include mortality, exposure to hazardous materials and increased risk of industrial accidents. For communities near development and production sites the major stressors are air pollutants, ground and surface water contamination, truck traffic and noise pollution, accidents and malfunctions, and psychosocial stress associated with community change. Despite broad public concern, no comprehensive population-based studies of the public health effects of UNG operations exist. Major uncertainties are the unknown frequency and duration of human exposure, future extent of development, potential emission control and mitigation strategies, and a paucity of baseline data to enable substantive before and after comparisons for affected populations and environmental media. Overall, the current literature suggests that research needs to address these uncertainties before we can reasonably quantify the likelihood of occurrence or magnitude of adverse health effects associated with UNG production in workers and communities.

I. INTRODUCTION

The U.S. holds large reserves of on-shore natural gas in many regions, including but not limited to the Barnett Shale in Texas, the Denver-Julesberg Basin in Colorado, and the Marcellus Shale in the northeast.[1,2] Technological advances in directional and horizontal drilling and hydraulic fracturing (referred to herein as unconventional natural gas, UNG) have eased access to shale and tight gas reserves that were previously uneconomical to recover, resulting in a "shale gas boom" at the beginning of the 21st century.[3,4] In the U.S., the number of UNG wells rose from 18 485 in 2004 to 25 145 in 2007 and it is estimated that over 11 000 wells are hydraulically fractured each year.[5,6] As of 2011, 95% of the natural gas consumed in the U.S. was produced domestically and production is projected to increase from 23 trillion cubic feet in 2011 to 33.1 trillion cubic feet in 2040, with almost all the projected growth in UNG production.[7] The most recent worldwide estimates of natural gas reserves are 2.6−5.7 times greater than what was estimated in the 1990s.[8]

As UNG development grows, it is expected to become more common near where people live and work, increasing the likelihood of human exposure to associated pollutants and related chemical and nonchemical stressors as well as transport of pollutants to nearby cities.[1,9−13] With any fossil fuel development, there is a potential for release of air and water pollutants, physical and public safety hazards, and a range of psychosocial stressors. At present the potential risks from UNG development are more uncertain than risks from conventional natural gas development.[1,6,10,12−19] This is because hydraulic fracturing fluid contains potentially hazardous chemicals, well fracturing requires large volumes of water and sand, and the overall process creates air pollution and large volumes of wastewater containing dissolved chemicals and contaminants of subterranean origin.[4] While unconventional technologies allow for consolidation of several wells on one well pad, multiwell pads focuses an intense industrial activity in one area for several months.[3,12] To maintain gas flows, wells may also be fractured more than once.[3,20] Because UNG development is a recent phenomena, relatively little peer-reviewed public health research exists. Nonetheless, there are potential health risks because production is rising and increasingly occurring near where people live and development is transforming both the population and character of nearby communities.[1,10,12,21] The lack of research on population health effects has led to broad public concern about the potential consequences of the UNG development process.

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Table 1. Relationships between Sources, Processes and Hazards That May Lead to Human Exposure, Health Effects or Population Health Effects[a]

		chemical hazards					
source	process	air	ground water	surface water soil/ sediments	physical hazards	safety hazards	water scarcity hazard
large trucks	all	DE			noise, vibration	spills and accidents	
heavy equipment	well pad construction, drilling, and well abandonment	DE			noise, vibration	spills and accidents	
dust	well pad construction, well abandonment	PM					
drilling mud	drilling	DMV	DM	DM			
fracturing fluid	hydraulic fracturing, flowback	Silica, FFV	FF	FF		spills	removes water from hydrological cycle
generators	drilling, hydraulic fracturing	DE			noise		
produced water	drilling and construction, flowback	DMV, PHC	DM, PHC, IN	DM, PHC, IN		spills	
drill cuttings	drilling and construction	PM, DMV, PHC	DM, PHC, IN	DM, PHC, IN		spills	
flowback water	flowback	FFV, PHC	FF, PHC, IN	FF, PHC, IN			
deep injection	flowback				seismic activity		
gas venting	drilling, flowback, production	CH_4, H_2S, PHC				accidents	
gas flaring	drilling, flowback, production	NO_X, CO_2,			noise		
pigging[b]	production	CH_4, PHC				accidents	
pipelines	production	CH_4, PHC				accidents	
condensate tanks	production	CH_4, PHC					

[a]**CH_4**: methane; **CO_2**: carbon dioxide; **DE**: diesel emissions, including particulate matter (**PM**), nitrogen oxides (NO_x), polyaromatic, aliphatic, and aromatic hydrocarbons, aldehydes, and sulfur dioxides (SOx); **DM**: drilling muds, e.g., boric acid, borate salts, rubber-based oil, synthetic oil; **DMV**: drilling Muds, Volatile, e.g., rubber-based oil, synthetic oil, aluminum tristearate, choline chloride; **FF**: fracturing fluids, e.g., lauryl sulfate, guar gum and others (see Table 2); **FFV**: fracturing fluids, volatile: e.g., glutaraldehyde, ethylene glycol, methanol,, petroleum distillate; **H_2S**: hydrogen sulfide; **IN**: inorganic chemicals; barium, strontium, bromine, heavy metals, salts and NORM (naturally occurring radioactive materials); **NO_X**: nitrogen oxides; **PHC**: aromatic and aliphatic petroleum hydrocarbons. Refs: King, G.E., Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells. *SPE Hydraulic Fracturing Technology*; Woodlands, TX, 2012; Jiang, M., et al. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ. Res. Lett.*. 2011. 6(3); United States Department of Energy, *Modern Shale Gas Development in the United States: A Primer*; Oklahoma City, OK, 2009. [b]The process of using gauges to perform maintenance on gas lines without stopping the flow of gas in the pipe line.

This review takes a systems approach to exploring main sources, hazards, exposures, and potential population health effects associated with UNG development in the US. We summarize the strengths and limitations of the existing literature on exposure pathways, environmental media concentrations, and potential risks for workers and communities as well as evaluate existing and potential approaches for assessing population health effects. We also identify risk mitigation strategies and related public health research needs.

II. HAZARDS AND SCALE OF EXPOSURES

As with any complex industrial process, UNG development is a series of steps best viewed as a system: (1) well pad and infrastructure preparation; (2) drilling and construction of well pipelines and facilities; (3) hydraulic fracturing; (4) "flow back" of gas, fracturing fluids, and produced water during well completion; and (5) subsequent connection of the well to the natural gas distribution system.[3] During the 20−30 year production life of a well petroleum byproducts are collected for sale and wastes (e.g., drilling cuttings, flowback and produced water) are treated, recycled and/or disposed offsite. Table 1 summarizes the relationship between major sources, development processes and hazards that may lead to human exposures and health effects. In addition to the chemical, physical, and safety hazards specified in Table 1, Figure 1 outlines the major psychosocial stressors associated with UNG development that may affect the health of nearby populations.

Chemical and nonchemical stressors found in and around UNG development sites may affect both workers and communities. The overall effect of these stressors on population health depends on the hazards, exposure pathways, and temporal and spatial reach of each stressor and its impacts, which may range from the well pad to local, regional, and global scales. The key exposure pathways and health effects are governed by the rate of release, fate and transport, persistence, and frequency and duration of human contact with each stressor, as well as the human behavioral factors that increase or decrease the likelihood of exposure (Figure 1). At the well site itself, the most imminent potential public health effects are accidents and injuries to workers who may also be exposed to acute (e.g., H_2S) and chronic (e.g., silica) stressors.[6,22] Stressors that exert their impacts at the local scale include chemical

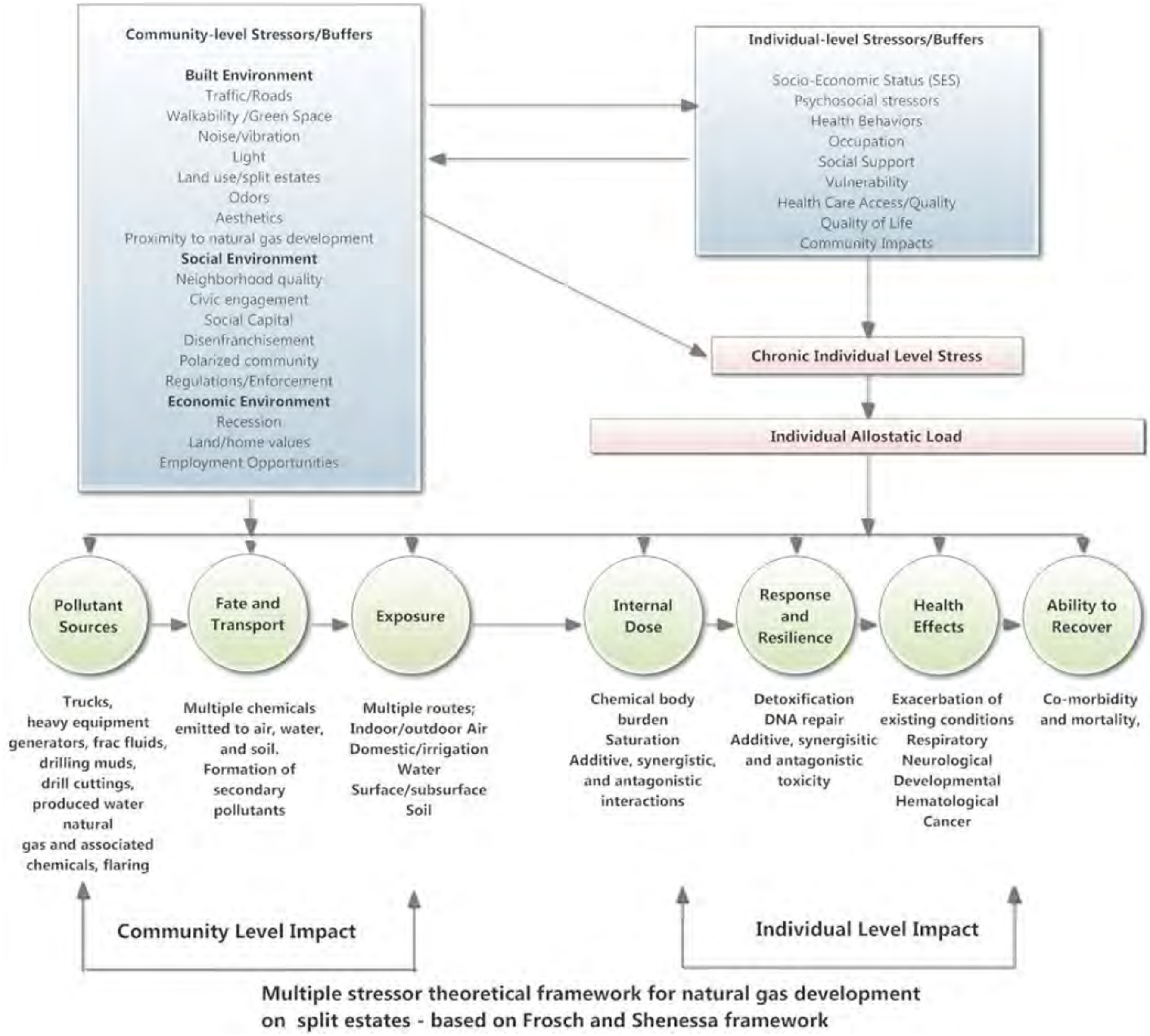

Figure 1. Allostatic load conceptual model describing community and individual level stressors and their relationship with psychosocial stress.

hazards transported offsite, such as volatile organic compounds (VOCs), diesel exhaust, fracturing fluids, and drilling and hydraulic fracturing wastes that migrate offsite through spills, leaks, or accidents (Table 1). Though there are potentially mitigating factors, such as increased tax revenue or income for leaseholders, nearby residents may complain of odors, noise, light, or psychosocial stress from declining land values or decreased housing availability.[10,23,24] The development of intracommunity differences in the perception of risk and rewards may also lead to stress in some residents.[25] Some local stressors may also be regional issues, such as water availability, ground level ozone, and water quality. At the global scale, the contribution of UNG development to methane and carbon dioxide levels in the atmosphere has broad implications for population health.[26,27]

The following sections describe existing mortality and morbidity outcomes that may stem from the major chemical, physical and psychosocial stressors that exist in and around UNG development as well as the pathways by which these stressors may affect workers and communities.

III. EXPOSURE PATHWAYS AND HEALTH EFFECTS

A. Occupational. *1. Fatalities and Injuries.* Industrial incidents, malfunctions, and worksite and traffic accidents put workers at increased risk of exposure to fires, explosions, and uncontrolled chemical releases. While there are no data specific to UNG production, data on the oil and gas industry indicate that it has a high occupational fatality rate. Between 2005 and 2009, the fatality rate was two and a half times the rate in the construction industry and 7-fold higher than the general industry rate.[22,28] Bureau of Labor Statistics data indicate that the fatality rate for oil and gas workers was more than 8-fold higher than in other occupations.[28] Nearly a third of the deaths were due to traffic accidents and single-vehicle rollovers were the most common accident type. Mortality rates are also related to the size of the company, with smaller companies having higher fatality rates compared to medium and large-sized

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operators.[29] Although the mortality rate data are aggregated across petroleum and natural gas workers, state-level data collected in Wyoming during the recent gas production boom suggest that the recent increase in natural gas development had a major impact on mortality trends. Between 2001 and 2008, Wyoming had 32 fatalities from drill rig accidents and 25 transportation-related fatalities in the oil and gas sector.[30] Wyoming also had the highest workplace fatality rate in the country in five of the six years between 2003 and 2008, and in 2010 its occupational fatality rate was three and half times the national average.[30,31] In contrast to worksite fatalities, nation-wide rates of reportable injuries in the oil and gas industry were ~3 folder lower than in the construction industry, though this may be a result of under-reporting.[16,22,28] Under-reporting would be consistent with the findings of Mendeloff and Burns (2012), who found an unexpected negative correlation between reported fatalities and nonfatal injuries in the similarly decentralized construction industry, which the authors suggest was due to under-reporting of nonfatal injuries when fatalities were high.[32]

2. Air Pollution. Unconventional natural gas development and production workers are at risk from air pollution exposure because they work in and around major emission sources. Air pollution from UNG development originates from (1) direct and fugitive emissions of methane and nonmethane hydro-carbons from the well and associated infrastructure (e.g., production tanks, valves, pipelines, and collection and processing facilities); (2) diesel engines that power equipment, trucks, and generators; (3) drilling muds, fracturing fluids, and flowback water; and (4) deliberate venting and flaring of gas and related petroleum products.

Hydrogen sulfide (H_2S), which is naturally occurring in natural gas reserves, is an explosion risk and is arguably the greatest acute toxicity hazard for natural gas workers.[33−35] Significant irritant and other central nervous system health effects occur at or above 100 ppm, and these effects gradually increase in severity with duration of exposure, with immediate death occurring at ~1000 ppm.[34] Little data exist on the frequency of occupational exposure to H_2S, but many companies require use of alarmed personal monitors to prevent fatalities.[16,22]

Among the hundreds of chemicals used to drill and fracture wells, silica is the most common additive to the process. Silica is also one of the key occupational hazards for workers because mechanical handing of crystalline silica, which is used as a proppant during hydraulic fracturing, creates large clouds of respirable dust.[16,36] Esswein et al.'s recent study of workers in Colorado, Texas, North Dakota, Arkansas, and Pennsylvania found that 8 h time weighted average breathing zone silica concentrations in 111 samples ranged from 0.007 mg/m^3 to 2.76 mg/m^3.[37] Nintey-three (84%) of the samples exceeded the American Conference of Industrial Hygienists threshold limit value (TLV) of 0.025 mg/m^3, 76 (68%) exceeded the National Institute of Occupational Safety and Health (NIOSH) recommended exposure limit (REL) of 0.05 mg/m^3, and 57 (51%) exceeded the Occupational and Safety Health Administration's (OSHA) current permissible exposure limit (PEL) for respirable silica-containing dust. Increasing evidence of the toxicity of silica has led OSHA to recently propose dropping its PEL to match the NIOSH REL.[38] Respirable silica can cause silicosis and lung cancer and has been associated with tuberculosis, chronic obstructive pulmonary disease (COPD), kidney disease, and autoimmune disease.[16] Exposure to silica dust also poses a hazard to workers in industries supporting shale gas development, such as sand mining and transport.[39]

Workers also may be exposed to petroleum hydrocarbons, such as aromatics (e.g., benzene, toluene, ethyl benzene, and xylenes; hereafter BTEX) and aliphatic compounds during well development and production.[27] The health effects most often associated with benzene include acute and chronic non-lymphocytic leukemia, acute myeloid leukemia, chronic lymphocytic leukemia, non-Hodgkins lymphoma, anemia and other blood disorders and immunological effects.[40,41] Occupa-tional exposure to petroleum compounds is also associated with increased risk of eye irritation and headaches, asthma symptoms, and multiple myeloma and non-Hodgkins lympho-ma.[42−47] Many of the common petroleum hydrocarbons measured in and around UNG sites, such as BTEX, have robust toxicity databases and health-based standards, while toxicity information for others, such as heptane, octane, and diethylbenzene, is more limited, thereby hampering the assessment of risks for these compounds.[48]

We found no published studies on exposures of UNG workers to other compounds used on site, though there are potential exposures from vaporization or aerosolization of drilling muds and hydraulic fracturing fluids that contain a range of neurological, respiratory and skin toxicants.[14,49−51] Workers are also exposed to diesel exhaust emitted from trucks and generators used to power operations. While diesel exhaust emissions vary by engine type and controls, exposure to diesel exhaust in other industries is associated with respiratory and cardiovascular disease.[52−54] The International Agency for Research on Cancer has classified diesel exhaust as a human carcinogen, while U.S. EPA classifies it as likely to be carcinogenic in humans.[41,55]

There is relatively little published research on other occupational stressors associated with UNG development, such as particulate matter from diesel engines or other combustion sources. Noise exposure is a significant hazard due to the presence of multiple sources, including heavy equipment, compressors, and diesel powered generators. Loud continuous noise has health effects in working populations.[56] It is likely that exposure to noise is substantial for many workers, and this is potentially important for health because drilling and servicing operations are exempt from some sections of the OSHA noise standard.[22] In addition to these direct exposures, peri-occupational issues, such as incidents of childhood lead poisoning from "take home" exposure to pipe dope on work clothes, increased rates of sexually transmitted infections, and steep increases in the demand for and price of rental housing are all adverse outcomes related to the rapid increase in the workforce in locales where development is occurring.[10,23,51] These work and life issues are addressed in greater depth in the Community effects section.

B. Community. While workers may be exposed to a wide range of hazards during well development, residents and community members living, attending school and working adjacent to UNG development sites may experience many of the same chemical or physical exposures. Although concen-trations in the environment are likely lower further from development sites, the round-the-clock development cycle means that cumulative exposures may be of concern for people living near UNG development activities.

1. Accidents and Injuries. Reports to state agencies indicate that traffic and industrial accidents occur in the course of UNG development and operations.[23,57,58] Increased truck traffic in residential areas raises the likelihood for traffic accidents and may decrease residents walking and exercising in areas of development.[12] The average multistage well can require hundreds to more than a 1000 truck round trips to deliver equipment (e.g., bulldozers, graders, pipe), chemicals, sand, and water needed for well development and fracturing.[13,59] Truck counts in Bradford County, PA, for example, were approximately 40% higher than a comparable 5-year average prior to UNG development, with a proportional increase in accidents involving large trucks. [59] Preliminary analysis of data from the Pennsylvania Department of Transportation's Crash Reporting System indicates a significant increase in the number of total accidents and accidents involving heavy trucks between 1997 and 2011 in counties with a relatively large degree of shale gas development compared to counties with no development.[58] Similarly, the Texas Department of Transportation noted a 40% increase in reported fatal motor vehicle accidents from 2008 to 2011 in 20 Eagle Ford Shale counties.[57] Additional research on the impact of increased truck traffic on residential accident and fatality rates is needed.

While not extensively addressed in the peer-reviewed literature, industrial accidents and natural disasters involving well infrastructure and pipelines may put nearby residents at increased risk of exposure to fires, explosions and hazardous chemicals, which is a concern in many communities.[23] The September 2013 catastrophic flood in northeastern Colorado, for example, resulted in 13 notable releases of oil, totaling 43 134 gallons, and 17 releases of produced water, totaling 26 385 gallons.[60] The limited monitoring conducted after the flood indicated that the releases were extensively diluted to concentrations below detection limits by the large volumes of floodwater, and that bacterial contamination of water supplies due to nonfunctional water treatment plants was likely a bigger public health concern than spills originating from petroleum development infrastructure.[61]

2. Air Pollution. Increased traffic from industrial operations can degrade air quality due to diesel exhaust, road dust, and nitrogen oxides (NOx) (Table 1). In addition to traffic-related pollutants, people living near UNG development sites may be exposed to VOCs, silica, and other chemicals used during fracturing and well completion as well as fugitive emissions of VOCs from pipes and valves. While there are few studies characterizing the emission and distribution of pollutants from well pads, there are many documented instances of odor complaints and increased air concentrations of VOCs and other compounds at or near well pads during development.[25,62,63] People living within $^1/_2$ mile of a multiwell pad complained of odors during well completions in Garfield County, CO, and 81% of respondents to a self-reporting survey in active shale gas development areas in Pennsylvania reported odors.[15,62] Hydrogen sulfide has a very low odor threshold and a 10 h half-life, so it may be responsible for some odor complaints.[34]

Pilot studies in Colorado's Piceance Basin, Pennsylvania's Marcellus, and Texas's Barnett Shale indicate that VOCs, including C2−C8 alkanes, aromatic hydrocarbons, methyl mercaptan, and carbon disulfide, are emitted during well completions as well as from compressors, condensate storage tanks and related infrastructure.[17,64−66] Natural gas development may be the primary source of ambient benzene concentrations in the Dallas Fort Worth Area and Garfield County, CO.[17,67] One of the few community pollution studies with near-well pad measurements during well completion found that VOCs were detected more often and at higher concentrations compared to regional ambient air samples.[15] In that study, benzene concentrations ranged from 0.94 to 69 $\mu g/m^3$ and C_5 to C_8 aliphatic hydrocarbon concentrations ranged from 24 to 2700 $\mu g/m^3$ in 24 samples collected 130 to 500 feet from the center of five well pads in western Colorado during the high-emission period of uncontrolled flowback. A second study in western Colorado collected 24 h integrated air samples 0.7 miles from a well pad and found that emissions were higher during drilling compared to levels found during a closed loop ("green") completion.[36] A study in eastern Colorado collected 36, 3 h integrated air samples during morning hours at 850 and 1650 feet from a well pad during a green completion.[68] Benzene concentrations ranged from 0.73 to 2.06 $\mu g/m^3$, and the highest toluene and speciated nonmethane organic carbon concentrations were observed when multiple trucks were at the well pad.[69] In addition to these three studies, regional scale air quality studies suggest that oil and gas operations are a significant source of ambient benzene and alkanes on the northern Colorado Front Range.[70,71]

Studies in Texas, Oklahoma, and Colorado have attributed emissions of light alkanes from oil and gas development to the formation and transport of ozone to nearby urban areas.[70−72] Ground level ozone concentrations in the Haynesville Shale region of East Texas and Louisiana are projected to increase by up to 9 and 17 ppb under low- and high-emission scenarios, respectively. The area affected by high ozone levels under the high-emission scenario is twice that of the low-emission scenario.[73] Increases in ozone levels in either scenario are sufficient to push some counties in the study area beyond the current U.S. EPA 8 h National Ambient Air Quality Standard (NAAQS) for ozone (75 ppb). Monitoring in the Dallas Fort Worth area indicates that decreases in mean annual 8 h ozone concentrations from 1997 to 2011, which coincided with dramatic increases in the number of shale gas wells after about 2007.[65] Additional study is needed to determine if this trend is attributable to decreasing emissions from unconventional gas development or if controls on other sources of VOCs are responsible for the observed change.[74,75] A modeling study of the Barnett Shale region of Texas predicts that VOC emissions associated with compressor engines and NOx emissions from flaring natural gas could increase peak 1 h ozone concentrations by up to 3 ppb and 8 h concentrations by several ppb.[76] A group at Rand Corporation has developed estimates of air emissions from operations related to the shale gas industry in Pennsylvania and utilized an EPA model to monetize estimated health effects. Their region-wide estimate of damages was \$7.2−35 million in 2011. Of note is that aggregate NOx emissions in some counties were 20−40 times higher than allowable for a single minor source.[77] Researchers in Colorado are conducting comprehensive studies designed to characterize shale gas emissions, with results expected in 2014 and 2015.[78]

Winter ozone concentrations above the 8 h NAAQS were observed in relatively remote areas in Utah's Uintah Basin and Wyoming's Upper Green River Basin in recent years.[79−81] Peak ozone concentrations reached 149 ppb and 8 h averages reached 134.6 ppb in the Uintah basin, and emissions inventories indicate that oil and gas operations were responsible for 98−99% of the VOCs and 57−61% of the NOx ozone precursors.[82] In the Upper Green River Basin, photolytic ozone production resulted in peak ozone concentrations >140 ppb when NOx and VOCs from the production of UNG become trapped at the surface by intense, shallow temperature inversions.[80] A modeling study indicates that wintertime ozone production in this region is most sensitive to VOC emissions, suggesting that emission controls on UNG development will likely play an important part in addressing concerns about elevated ozone.[83]

The recent Allen et al. study examining methane releases during the drilling cycle of cooperating industries in different areas of the United States is also pertinent to community air pollution.[84] The study observed a very wide range of total methane emissions as well as a wide range in the rate of release for wells right next to each other that were developed by the same company. Methane emissions during the flowback period ranged from 0.01 to 17 Mg, and the rate of methane emissions during an uploading event varied by about 100-fold. While the authors did not measure BTEX or other VOCs, it is likely that the same degree of variability would be expected for these compounds assuming they are emitted with the measured methane. The work of Allen et al. suggests that local hot spots of both methane and possibly nonmethane air pollutants exist. As not all companies or production areas have cooperated with methane emission measurements, and as emission control practices vary across the industry, there is legitimate concern that local air pollution may produce adverse effects in individuals who live near the high emitting sites or processes.[85]

Apart from the direct effects of these pollutants on human health, UNG development also has the potential to positively or negatively affect global climate. Burning natural gas is far more energy-efficient than burning other fossil fuels, particularly coal, and results in lower emissions of carbon dioxide.[86] Methane itself is a potent greenhouse gas and any released to the atmosphere that otherwise would be locked up underground contributes to global climate change. Direct methane emissions occur during drilling and well completion, and fugitive methane emissions occur along pipelines, valves, and other related infrastructure. Although controversial, the emerging consensus in the scientific literature is that the advantage conferred by burning natural gas is a net benefit compared to burning coal, even considering methane losses to the atmosphere from UNG production.[70,84,87−93] Any further reduction in direct and fugitive methane emissions would be a further net benefit if natural gas permanently replaces coal that otherwise would be produced and burned.

3. Water Pollution. Intense public interest has been focused on possible contamination of drinking water sources with hydraulic fracturing chemicals and other pollutants associated with drilling and production (Tables 1 and 2). Potential pathways of surface and groundwater contamination from UNG development are transportation spills, well casing leaks, migration through fractured rock, abandoned wells, drilling site discharge, and wastewater disposal.[94]

The existing scientific literature has limited information indicating that UNG development may contaminate domestic ground or surface water supplies for individuals or communities.[19,95] Direct attribution of contamination from the fracturing process is hindered by lack of baseline data, the widespread presence of methane and petroleum byproducts in many gas-bearing basins, and nondisclosure agreements that limit the reporting of contamination after legal settlements.[1,3,96] Current scientific consensus is that accidents and malfunctions, such as well blowouts, leaking casings, and spills of drilling fluids or wastewater, are more likely to contaminate surface and groundwater supplies than the process of high-volume hydraulic fracturing itself.[19,94]

Table 2. Types of Additive, Example Chemicals, And Their Purpose in the Hydraulic Fracturing Process[a]

additive	example chemical	purpose
acid	hydrochloric or muriatic acid	helps dissolve minerals and initiate cracks in the rock
antibacterial agent	glutaraldehyde	eliminates bacteria in the water that produces corrosive byproducts
breaker	ammonium persulfate	allows a delayed break down of the fracturing gel
clay stabilizer	potassium chloride	brine carrier fluid
corrosion inhibitor	n,n-dimethyl formamide	prevents corrosion of pipes
cross-linker	borate salts	maintains fluid viscosity
defoamer	polyglycol	lowers surface tension and allows gas escape
foamer	acetic acid (with NH_4 and $NaNO_2$)	reduces fluid volume and improves proppant carrying capacity
friction reducer	petroleum distillate	minimizes friction in pipes
gel guar gum	hydroxyethyl cellulose	helps suspend the sand in water
iron control	citric acid	prevents precipitation of metal oxides
oxygen scavenger	ammonium bisulfate	maintains integrity of steel casing of wellbore; protects pipes from corrosion by removing oxygen from fluid
pH adjusting agent	sodium or potassium carbonate	adjusts and controls pH of the fluid
proppant	silica, sometimes ceramic particles	holds open (props) fractures to allow gas to escape from shale
scale inhibitor	ethylene glycol	reduces scale deposits in pipe
solvents	stoddard solvent, various aromatic hydrocarbons	improve fluid wettability or ability to maintain contact between the fluid and the pipes
surfactant	isopropanol	increases viscosity of the fracturing fluids and prevents emulsions

[a]Sources: Colborn, T., et al. Natural Gas Operations from a Public Health Perspective. *Human and Ecological Risk Assessment: An International Journal*. 2011. 17(5): p. 1039−1056; Earthworks. *Hydraulic Fracturing 101*. 2011 [cited 2012 Jan 11] Available from: http://www.earthworksaction.org/issues/detail/hydraulic_fracturing_101; Encana Corporation. Chemical use. [cited 2013 Sep 25] Available from: http://www.encana.com/environment/water/fracturing/chemical-use.html; EnergyIndustryPhotos. What is Hydraulic Fracturing and What is it Used for? . 2008 [cited 2012 Jan 11] Available from: http://www.energyindustryphotos.com/what_is_hydraulic_fracturing.htm; King, G.E., Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells. *SPE Hydraulic Fracturing Technology*; Woodlands, TX, 2012; Jiang, M., et al. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ. Res. Lett.*. 2011. 6(3); United States Department of Energy, *Modern Shale Gas Development in the United States: A Primer*; Oklahoma City, OK, 2009.

Aside from accidents and malfunctions, the evidence for contamination of groundwater wells with methane, fracturing chemicals, or other process wastes is mixed.[97−100] EPA studies in Pavilion, Wyoming, and Dimmick, Pennsylvania that have suggested associations between UNG development and drinking water contamination are controversial because of uncertainties about whether the chemicals present in these aquifers are there as a result of the hydraulic fracturing process.[96,101,102] Residents of both towns have been provided replacement drinking water by authorities.[101] An extensive report by the Ground Water Protection Council exploring drinking water contamination from UNG development in Texas and Ohio found evidence of leakage from orphaned wells and disposal pits, but no evidence of contamination from site preparation or the well stimulation process.[85] Osborn et al. used a convenience sampling approach to explore water quality in 60 samples collected in areas of active drilling in the Marcellus Shale.[18] While they did not find evidence of hydraulic fracturing chemicals in their samples, they did find that methane levels were higher in drinking water wells closer to UNG wells. Similarly, analysis of private well water quality in aquifers overlying the Barnett Shale has revealed that arsenic, selenium, strontium and total dissolved solids (TDS) exceeded the EPA's maximum contamination limit (MCL) in some samples located within 3 km of active natural gas wells.[103] Overall, the existing peer-reviewed literature lacks studies with substantive comparisons of water quality before and after natural gas development due to a lack of baseline data on water quality prior to the advent of UNG development. There is at least one documented case of contamination of water supplies from abandoned natural gas wells, but a comprehensive analysis of the effect of plugged or abandoned wells as a potential exposure pathway is a research need.[104]

Produced water is the largest component of the UNG development waste stream and is distinct from flowback water, which is primarily fracturing fluids that come out after immediately after well stimulation.[105,106] Produced water is water present in gas-bearing formations that comes to the surface over the life of the well . Given the high pressure and temperature in the underlying strata, both flowback and produced waters have the potential to contain transformation products that originate from the drilling muds and fracturing chemicals as well as methane, petroleum condensate, salts, metals, and, depending on the formation, naturally occurring radioactive materials (NORM). Flowback and produced water is stored in surface pits or sealed tanks prior to reuse and/or disposal.[87] Studies assessing composition of Marcellus Shale produced water found that most metals and salt ion concentrations increased with time after fracturing and were correlated with the composition of the underlying strata.[107,108] Current evidence suggests that wastewater is more effectively treated onsite because effluents discharged to publicly owned treatment plants may not be able to provide sufficient treatment for this waste stream.[109,110]

Potential for groundwater contamination from surface spills at wastewater storage and treatment facilities at active well sites has received increased attention. From July 2010 to July 2011, Gross et al. noted 77 reported surface spills (~0.5% of active wells in the region) impacting the groundwater in Weld County, CO.[111] Measurements of BTEX exceeded EPA maximum contaminant limits in most cases, and actions taken to remediate the spills were effective at reducing BTEX levels.[111]

C. Potential Health Effects and Population-Based Studies. At present, there are no population-based studies of health effects from water contamination, and relatively few studies exploring the impact of airborne exposures. Nonetheless, the potential for health effects can be inferred for specific chemicals from known health effects of contaminants if data exist on their potential potency that can then be linked to measured or estimated human exposure.

Exposure to ozone is associated with several adverse health effects, including respiratory, cardiovascular, and total mortality as well as decreased lung function, asthma exacerbation, COPD, cardiovascular effects and adverse birth outcomes.[112] People with asthma, children, and the elderly are at increased risk, and adverse health outcomes have been observed at concentrations as low as 41 ppb.[112] The overall relationship between ozone concentration and response to multiple outcomes appears to be linear with no indication of a threshold.[112] While there are many studies documenting the health effects of ozone exposures and several studies that suggest an association between unconventional oil and gas development and ground level ozone production, we found only one population-based study on ozone- and health effects in a UNG development region. That study found that between 2008 and 2011, Sublette County, Wyoming observed a 3% increase in the number of clinic visits for adverse respiratory-related effects for every 10 ppb increase in the 8 h ozone concentration the previous day.[113]

Populations living near UNG operations report odors and, in some cases, upper respiratory, neurological, and dermatological symptoms.[1,23,62,114] While these studies lack scientific rigor because they are volunteer or convenience samples of the local population, these effects are consistent with known health effects associated with petroleum hydrocarbons exposure. For example, inhalation of trimethylbenzenes and xylenes can irritate the respiratory system with effects ranging from eye, nose, and throat irritation to difficulty in breathing and impaired lung function.[115,116] Inhalation of xylenes, benzene, and aliphatic hydrocarbons can adversely affect the nervous system with effects ranging from dizziness, headaches, fatigue, and limb numbness to a lack of muscle coordination, tremors, temporary limb paralysis, and unconsciousness at high levels.[40,115−119] Maternal exposure to ambient levels of benzene has been associated with an increase in birth prevalence of neural tube defects.[120]

There is a growing epidemiological literature on the health effects associated with UNG development. A retrospective study of 124 862 births in rural Colorado indicated an association between maternal proximity to natural gas well sites and birth prevalence of congenital heart defects and neural tube defects, but no association with oral clefts, term low birth weight or preterm birth.[121] A working paper exploring 1 069 699 births in Pennsylvania reported increased prevalence of low birthweight and small for gestational age births, as well as reduced appearance, pulse, grimace, activity, respiration (APGAR) scores in infants born to mothers living within 2.5 km of a natural gas well compared to infants born to mothers living further than 2.5 km from a well.[122] While these preliminary epidemiological studies are hindered by a lack of spatial and temporal specificity in exposure and individual level risk factors, they underscore the need for a better understanding of exposures and health effects in populations living in UNG development and production areas. Another study compared standardized incidence rates (SIRs) for childhood cancer in Pennsylvania counties, but found no difference in SIRs for all cancer types except central nervous system (CNS) tumors, which the authors attributed to a large number of excess tumors in counties with the fewest wells.[123] The scientific validity of this ecological study is questionable because it chose before and after comparison periods that are not relevant to current concerns about UNG development.[124] It is also limited by lack of an individual level assessment of relevant confounders and the assumption that individual exposures to hydraulic fracturing are uniform within a county or confined by county boundaries. Additional epidemiological studies are needed to shed light on the existence and nature of disease patterns that might be associated with UNG development.

D. Socioeconomic Impacts, Psychosocial Effects and Human Health. In addition to the potential for public health benefits from lower regional and global air pollution levels resulting from replacing coal with natural gas in power plants, there are potential economic benefits that could contribute to the overall health of a community.[125] Natural gas development may bring economic growth through increased employment. Though estimates are uncertain, unconventional oil and natural gas development is estimated to employ up to 1.7 million people in the U.S. and is projected to support nearly 3 million jobs by 2020.[126] Various reports and a leading industry association, America's Natural Gas Alliance (ANGA), state that the benefits of natural gas include local infusion of funds to leaseholders, jobholders, and the providers of ancillary services, as well as the economic value to the general public of lower prices of natural gas and electricity.[86,126−128]

There are also negative economic effects, however, which often fall on community members least able to bear the loss. A substantial body of literature indicates negative social effects from energy extraction in small "boomtowns" during the 1970s and 1980s that are similar to the 21st century UNG boom.[10]

Studies in Colorado and Canada finding increases in crime, substance abuse, and sexually transmitted infections corresponding to periods of increased natural gas development activity substantiate these concerns.[10,12,23,129] The influx of UNG industry workers has led to rapid rental price increases, particularly in rural counties with low populations and limited housing stock.[130] The effect has been greatest on low and fixed income individuals who can no longer pay for their homes. As a result, local social services, including the need to develop homeless shelters, may be strained.[131] Community resilience, defined as the ability of a community to sustainably utilize available resources to withstand, respond to, and/or recover from adverse events, may be affected by UNG development, as was evident when social services were further strained by a major storm in central Pennsylvania in 2011.[130] The economic value of lost ecosystem services in areas that rely on tourism and second homes has not been fully assessed, although one estimate suggests a loss of between \$11 and \$27 million per year in Pennsylvania.[132] A study in Washington County, PA, a semirural area, has reported at least a transitory loss in property values in areas immediately surrounding shale gas drilling sites.[130] In view of the broad social effects and the community divisiveness that has attended UNG development, health effects attributable to stress are not surprising and are consistent with previous studies of boomtowns.[10,127,133−136]

Many of the nonspecific symptoms associated with UNG development may reflect psychosocial stress. Contributing to this stress is a lack of trust and transparency concerning industry and government action. Ferrar et al. (2013) noted that those who believe their health has been affected report higher stress levels due to loss of trust and perceived lack of transparency. More than half these subjects report they have been denied or provided with false information (79%), that their concerns/complaints have been ignored (58%), and that they are being taken advantage of (52%).[25] It is notable that these psychosocial stressors are reported more frequently than physical stressors such as noise (45%) and odors (13%). Perceived secrecy about hydraulic fracturing agents and the makeup of produced water are contributing to this lack of trust.[130] Social amplification of risk perception is commonly noted in situations in which there is a lack of trust.[137,138] A recent review of the many factors involved in risk perception found that the two major determinants were familiarity and trust; with other factors, such as gender, age, media coverage, and socioeconomic status being far less important.[139]

IV. HEALTH RISKS FROM SHALE GAS DEVELOPMENT

To date observational studies exploring the association between human health and UNG development have had a number of scientific limitations, including self-selected populations, small sample sizes, relatively short follow-up times and unclear loss to follow-up rates, limited exposure measurements and/or lack of access to relevant exposure data, and lack of consistently collected health data, particularly for noncancer health effects. Given these limitations, the lack of observational studies and the public's demand for answers, it is likely that human health risk assessments will be needed to provide projections of potential future harm for both short-term catastrophic and long-term human health risks.

Risk Governance, Risk Estimates, and Cumulative Risk. Natural gas development is governed by a mix of federal, state, and local laws and regulations.[1,13] The Federal government has relatively little direct authority over natural gas development and production, as the permitting authority lies with states and, in some cases, local authorities.[13] Companion papers in this volume address the key risk governance issues around UNG development, so we focus on the current estimates of public health risk and related issues and research needs.

Human health risk assessments published to date have focused on risks to communities from only air exposure. McKenzie et al.'s screening-level human health risk assessment is the only study to utilize measurements collected near well pads during the high emission well completion process, and found that residents living nearest to the well pad were at increased risk of acute and subchronic respiratory, neurological and reproductive effects.[15] They also estimated lifetime excess cancer risks, which were in the range of concern but below the range where action is typically taken. Other risk assessments conducted to date are largely in agreement with these observations, indicating slightly elevated excess lifetime cancer risks driven by benzene, some indication of acute or subchronic noncancer risks for those living closest to well sites, and little indication of chronic noncancer risks.[69,96,140−143] Few studies have attempted to use biomonitoring to explore risks from shale gas-related pollutants. Blood and urine samples collected from 28 adults living in Dish, Texas, a town with large numbers of gas wells, storage tanks, and compressor stations near residences, found no indication of community wide-exposure to VOCs.[144] These results likely reflect the multiple potential sources and the short half-lives of most VOCs in urine and blood, especially since the sampling did not coincide with known or perceived exposures, and concurrent air samples were not collected for study subjects.

This limited collection of risk studies underscores the overall lack of and need for substantive research on the human health effects stemming from UNG development. Given the broad range of chemical and nonchemical stressors present in and around UNG development sites and public demand for explication of the real and perceived risks, more substantive cumulative risk research is needed to address public concerns about the effects of UNG development on human and ecosystem health.[145,146] Figure 1 outlines a potential cumulative risk assessment approach that incorporates chemical, physical, and psychosocial stressors that contribute to stress-related health effects in populations living near UNG development sites. This cumulative risk approach uses an allostatic load conceptual model to incorporate the various stressors and buffers that act on individuals and communities.[145,147] Additional research is needed to both produce cumulative risk estimates and judge their utility for local, state, and federal decision-makers.

V. PUBLIC HEALTH RESEARCH NEEDS

The major uncertainties that should be addressed in future research on the effects of UNG development are the magnitude and duration of human exposure to stressors as well as the lack of baseline data to enable substantive before and after comparisons in affected populations and environmental media.[13] Additional process uncertainties include the location and extent of future UNG development as well as the cost, feasibility, and success of future emission control and mitigation strategies. Overall, the current scientific literature suggests that there are both substantial public concerns and major uncertainties to address before we can reasonably quantify the likelihood of occurrence or magnitude of adverse health effects in workers and communities where UNG development will likely occur.

Occupational health and safety research needs include both disease surveillance and exposure characterization. This includes tracking of fatalities, injuries, and health effects data in a defined population of unconventional resource workers, with particular focus on benzene, toluene, and silica related disease, hearing loss, and other traffic and worksite safety issues as well as health-based standards for poorly characterized compounds, such as aliphatic hydrocarbons.[22,29] Exposure data is also needed in workers to characterize the magnitude, frequency, duration of exposure to the wide range of chemical and physical stressors present at the worksite. Measurements should focus on continuous exposure monitoring to characterize acute and chronic worker exposure to aliphatic and aromatic hydrocarbons, diesel exhaust, fracturing chemicals, silica, produced water, H_2S, NORM, and noise over the wide range of UNG development activities.

Given the lack of systematic tracking of exposure and health effects in communities, there are little data to inform risk mitigation and risk management activities. For air quality, key unknowns include characterization of baseline air quality prior to development in new areas as well as characterization of the variability in exposure during high emissions processes, specifically drilling, hydraulic fracturing, and well completion activities. For water quality, unknowns include characterization of baseline water quality and impacts during each of the process steps that use water, that is, chemical mixing, hydraulic fracturing, flowback, and storage of flowback and produced water and wastewater treatment and disposal. Research on other stressors, including noise and light, traffic, and other safety hazards needs to be conducted in the context of understanding the overall effect of the mixture of these chemical and physical stressors. The interaction with the stress created by rapid change and community disruption is a key research need for characterizing health effects in locales where development is encroaching. Better understanding of cumulative risk issues will help inform UGD control policies and mitigate adverse community effects.[148]

At present, relatively little funding for independent research is available from federal, state, foundations, industry, or public-private partnerships to address these public health research needs. Given the high level of mistrust observed between citizens and the natural gas development industry it is important that research is designed and conducted by scientists that are not perceived as biased in favor of or against the industry.[95] Public-private partnerships (e.g., the Health Effects Institute) that solicit and fund rigorous research are a model that has worked for contentious public health issues in the past and may be effective in the future.

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Notes

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LIST OF ACRONYMS

APGAR	appearance, pulse, grimace, activity, respiration
BTEX	benzene, toluene, ethyl benzene, xylenes
CNS	central nervous system
COPD	Chronic obstructive pulmonary disease
H_2S	hydrogen sulfide
MCL	maximum contamination limit
Mg	megagram
NAAQS	National Ambient Air Quality Standard
NIOSH	National Institute of Occupational Safety and Health
REL	recommended exposure limit
NOx	nitrogen oxides
NORM	naturally occurring radioactive materials
OSHA	Occupational and Safety Health Administration
PEL	permissible exposure limit
SIR	standardized incidence rate
TDS	total dissolved solids
TLV	threshold limit value
UNG	unconventional natural gas
U.S. EPA	United States Environmental Protection Agency
VOC	volatile organic compound

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Exhibit 38.03

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Sources of air pollution in a region of oil and gas exploration downwind of a large city

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HIGHLIGHTS

- 6 volatile organic carbon sources are resolved from autoGC and PTR-MS measurements.
- 3 organic aerosol classes are resolved from aerosol mass spectrometer measurements.
- Insights into the organic aerosol sources are gained from VOC sources.
- Reactivities suggest biogenic and oxidized VOCs contribute significantly to ozone.
- Reactivities suggest oil and gas emissions contribute incrementally to local ozone.

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ABSTRACT

The air quality in the outflow from Fort Worth, TX was studied in June 2011 at a location surrounded by oil and gas development in the Barnett Shale. The objectives of this study were to understand the major sources of volatile organic compounds (VOCs) and organic aerosols and explore the potential influence each VOC source had on ozone and secondary organic aerosol formation. Measurements of VOCs were apportioned between six factors using Positive Matrix Factorization (PMF): Natural Gas (25 ± 2%; ±99% CL); Fugitive Emissions (15 ± 2%); Internal Combustion Engines (15 ± 2%); Biogenic Emissions (7 ± 1%); Industrial Emissions/Oxidation 1(8 ± 1%); and Oxidation 2 (18 ± 2%). Reactivity calculations suggest the Biogenic and Oxidation 2 factors were the most likely VOC sources to influence local ozone. However, enough OH reactivity was calculated for factors related to the oil and gas development that they could incrementally increase O_3. Three organic aerosol (OA) types were identified with PMF applied to high-resolution time-of-flight aerosol mass spectrometry measurements: hydrocarbon-like OA (HOA; 11% of mass) and two classes of oxidized OA (semi- and less-volatile OOA, SV and LV; 45% and 44%, respectively). The HOA correlated with the Internal Combustion Engine VOC factor indicating that a large fraction of the HOA was emitted by gasoline and diesel motors. The SV-OOA correlated with the oxidized VOC factors during most of the study, whereas a correlation between LV-OOA and the oxidized VOC factors was only observed during part of the study. It is hypothesized that SV-OOA and the oxidized VOC factors correlated reasonably well because these factors likely were separated by at most only a few oxidation generations on the oxidation pathway of organic compounds.

1. Introduction

Air pollution from oil and gas development by hydraulic fracturing (better known as “fracking”) has affected air quality in some regions of the US (Carter and Seinfeld, 2012; Edwards et al., 2013). Development by fracking is being performed near residential areas in several locations in the US, and concerns have been raised over

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the impact of these operations on local air quality. Air pollutants emitted include volatile organic compounds (VOCs), nitrogen oxides (NO_x), carbon monoxide (CO), and organic aerosols (OA). Under appropriate atmospheric conditions, the VOCs and NO_x released can contribute to elevated ozone (O_3) concentrations (Edwards et al., 2013) and are likely to impact formation of secondary particulate matter. These species can originate from a variety of sources such as compressor engines, leaking valves on tanks and pipes, compromised pipe seals, well heads, flares, and fracking trucks (Armendariz, 2009).

The measurements described here were made in a region of oil and gas development in the Barnett Shale near Dallas-Fort Worth, TX (DFW). Air quality monitoring by the Texas Commission on Environmental Quality (TCEQ) within this area indicates that the largest O_3 mixing ratios often are observed to the northwest of the metroplex. The DFW metropolitan area (population ~6.5 M) is currently out of compliance with the O_3 National Ambient Air Quality Standard (NAAQS) (USEPA, 2013a). Though the reasons for the exceedances have not been elucidated fully, two hypotheses have been formed. The first is that elevated O_3 concentrations during the summer are caused solely by pollution transported from the urbanized area to the northwest. The second is that emissions associated with the oil and gas development enhance O_3 concentrations above those associated with the urban outflow.

This study explores the potential influence of VOCs emitted from the Barnett Shale development and the DFW metroplex on O_3 and organic aerosols. The VOCs emitted from oil and gas development and urban centers include alkanes, alkenes, and aromatics. While this list is only a subset of atmospheric VOCs, they are the most relevant to this study. Organic aerosols are a complex mixture of carbon-based compounds that are low enough in vapor pressure to exist partially or fully in the condensed phase (Jimenez et al., 2009; Donahue et al., 2011a; Donahue et al., 2011b; Chan et al., 2013). Freshly emitted aerosols, including those from the sources associated with oil and gas operations discussed previously, typically are composed of hydrocarbons, whereas compounds with oxygen and nitrogen heteroatoms are more prevalent in secondary OA (SOA, formed in situ from VOC oxidation products) or primary OA (POA) that has been aged by the atmosphere. In contrast to VOCs, direct emission of POA over land is dominated by human activities (Zhang et al., 2009; Rutter et al., 2014).

To achieve the objectives of this study, the sources of VOCs were inferred using the EPA Positive Matrix Factorization (PMF) model 3.0 which resolves source signatures contributing to environmental measurements (Norris et al., 2008). Next, the reactivities of the identified VOC sources with respect to the hydroxyl radical (OH) were calculated to provide insight into which sources may impact local O_3 formation in the outflow from DFW as it moves across the Barnett Shale. Finally, OA was apportioned into compositional classes using a special version of PMF for apportioning Aerosol Mass Spectrometer (AMS) data (Ulbrich et al., 2009), and the sources of these classes were considered based on the results from the VOC PMF.

2. Methods

2.1. Site description

The Eagle Mountain Lake (EML) site (Fig. S1) was located approximately 30 km northwest of the western edge of the DFW metroplex on flat Texas Air National Guard property (32° 59′16″ N, 97° 28′ 37″ W; +32.987891°, −97.477175°; 226 m above sea level) where a small but significant number of uncounted cattle are allowed to roam. The site is slightly to the west (~3 km) of a minor state highway (two lanes each way) and includes sparse trees and bushes. The surrounding area is sparsely populated, and EML itself is located just to the west (~2 km) of the site. Two small airports are located close to the site, the first to the east (~10 km) and the second to the west-southwest (~1 km). Numerous natural gas operations are in close proximity to the EML site (Fig. S1). As a result, EML is an appropriate location at which to make close-field measurements of primary emissions from natural gas operations. In addition, due to the prevailing wind (Fig. 1), measurements made at EML captured pollution in the urban outflow from FW after a few hours of advection and processing based on distance and wind speed. Predominant flow from the south-southeast was confirmed by Hybrid Single-Particle Lagrangian Integrated Trajectory modeling (Draxler and Rolph, 2013).

2.2. Measurements

The TCEQ operates a continuous air monitoring station at this location. Of most relevance to the work presented here are VOC data collected using an automated gas chromatograph (auto-GC); these data focus primarily on light hydrocarbons collected on an hourly basis. During June 2011, researchers from several institutions performed air quality measurements at EML to complement these auto-GC measurements. Measurements used in this study include aerosol composition measured with a high-resolution time-of-flight AMS (HR-ToF-AMS, Aerodyne, Billerica, MA), VOCs measured with a proton transfer reaction mass spectrometer (PTR-MS; IONICON Analytik, Innsbruck, Austria), particulate black carbon (BC) with an aethalometer (MicroAeth; AethLabs, San Francisco, CA), water soluble aerosol composition measured with a particle-into-liquid sampler (PILS, Brechtel Manufacturing, Inc., Hayward, CA) connected to two ion chromatographs (Dionex, Sunnyvale, CA), key trace gases (O_3, sulfur dioxide (SO_2) CO, and NO_x; Thermo Fisher Scientific, Sunnyvale, CA), planetary boundary layer heights (PBLH) measured with a ceilometer (Vaisala, Woburn, MA), and standard meteorological parameters (wind speed and direction, temperature, relative humidity, etc.) made with a variety of sensors. More detailed information about data collection is provided in the Supplemental Information (SI).

2.3. Reactivity calculations

Reactivity with respect to OH was calculated for each identified VOC source to probe its potential influence on local O_3 formation. The reactivity (s^{-1}) of an individual VOC i is defined as the product of k_i, the reaction rate coefficient of VOC i with OH at the given temperature (cm^3 $molec^{-1}$ s^{-1}), and the concentration of VOC i (molec cm^{-3}). PMF assumes that the relative contributions of individual of VOCs to a source factor j (χ_{ij}, from PMF results) are constant across the entire time period. As a result, the reactivity of VOC i from factor j (R_{ij}) can be found from the product of χ_{ij} and R_i. To find the reactivity of a given source (R_j), R_{ij} values are summed over all VOCs.

2.4. Positive matrix factorization

VOCs were apportioned between six sources using EPA PMF 3.0 (Norris et al., 2008). This model seeks co-variance in user-provided time series of concentrations of species (the uncertainties for which also are required) to determine statistically a set of factors that can be recombined to account for as much of the total measured mass as possible. Based on the predominance of species that fall into a given factor, it is possible to attribute that factor to a source. In addition, the user can determine which factor solution (five, six, seven, etc. factors) is most appropriate based on published factor

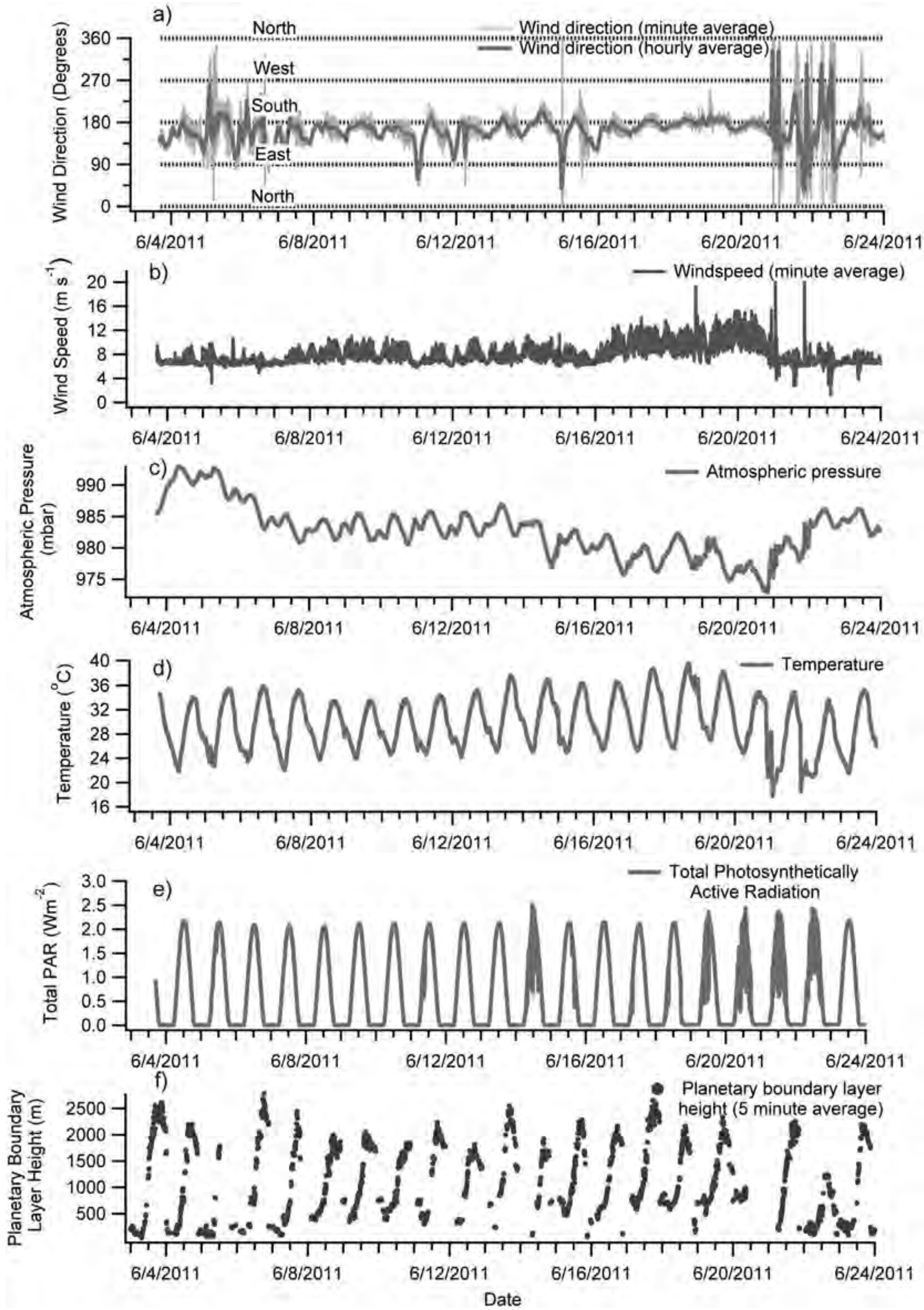

Fig. 1. Time series of meteorological parameters measured at Eagle Mountain Lake (CAMS 75) between 6/3/2011 and 6/23/2011. a.) Wind direction; b.) Wind speed; c.) Pressure; d.) Temperature; e.) Total PAR; f.) Boundary layer height.

compositions, model residuals, ratios of observed to predicted measurements, relationships of known tracers to sources, diurnal profiles, interpretation of structure in the time series, an understanding of the surrounding sources, and the meteorological conditions. A review of the PMF application is provided in the SI.

A separate PMF model was used with the HR-ToF-AMS data (Ulbrich et al., 2009). In this model representative spectra (assigned to various OA types) are determined as factors. Over the entire time series, the representative spectra that result in the minimization between observed and calculated spectra are determined. These spectra are then assigned to the various types of OA based on comparison to published PMF studies of AMS data and correlations to time series of other pollutants. Based on the linear combination of these spectral factors to yield the total spectrum, fractions of the total OA concentration are calculated and assigned to each OA type. This methodology results in time series of individual OA components as well as average spectra that describe each OA component.

2.5. Nomenclature

Historically, AMS OA factors resolved by PMF have been described using nomenclature such as hydrocarbon-like OA (HOA), oxidized OA (OOAI and II), low volatility (LV)-OOA, and semi-volatile (SV)-OOA to indicate the relative levels of oxidation or to identify a particular source type (Ulbrich et al., 2009; Zhang et al., 2011). These labels are qualitative and are not ideal for the comparison of factors derived from different studies. This is because the overall oxidation state of OA associated with an air mass is the result of a complex mixture of direct emission, formation of SOA from VOC precursors by various routes, heterogeneous oxidation of condensed-phase material, etc. For this reason, the OA components that are identified by PMF and labeled by an investigator as OOA I and OOA II in one study may not be exactly the same in composition as aerosols given the same designation in a different study or within different time periods within the same study. For this study, the terminology uses HOA, SV-OOA (less oxidized), and LV-OOA (more oxidized) for consistency with previous work.

3. Results and discussion

3.1. Meteorology

Meteorological conditions are summarized in Fig. 1. The campaign was characterized by winds from the direction of DFW (from the southeast) for much of the campaign, with increased variability during meteorological transitions. Wind speeds were between 1 and 21 m s^{-1} and averaged 8 m s^{-1}. Temperatures ranged between 18 °C and 40 °C, and conditions were sunny. The only precipitation occurred during a heavy thunderstorm on 6/21. The atmospheric pressure ranged between 973 mbar and 993 mbar. The observed pressure and thunderstorm activity show that a front passed over the site on 6/21. Back trajectories indicate that changes in meteorology were consistent with changes in air mass trajectories (Draxler and Rolph, 2013). The PBLH typically varied between 40 m and 1680 m during the early morning hours and between 1500 m and 2500 m in the afternoon, except on 6/22 when the afternoon maximum was 1200 m. Lower PBLHs were observed for long periods overnight from 6/3 until 6/7 and from 6/22 onwards, a characteristic not seen during the rest of the campaign.

3.2. Gas-phase and BC data overview

Overviews of measured CO, BC, SO_2, NO_x, and O_3 are given in Table 1 and Fig. S2. The concentrations of the primary gaseous pollutants (CO, SO_2, and NO_x) were typically low, with short-lived nocturnal increases interpreted as impacts from local point sources. The values observed were consistent with the rural nature of the measurement site and the presence of point sources upwind (USEPA, 2013b). An increase in NO_x due to lightning was also observed during the thunderstorm (Choi et al., 2005). The BC concentrations were similar to urban measurements (USEPA, 2012) and higher than expected considering the rural nature of EML, indicating the potential impact of sources close to the site. Daily maximum O_3 concentrations were generally higher during periods of high pressure and lower during the middle of the study period leading up to the thunderstorm on 21 June. On three days (6, 22, and 23 June) the 8-h O_3 concentrations exceeded the NAAQS of 75 ppb.

The subset of VOC concentrations presented (Table 2 and Fig. 2) are generally consistent with rural measurements (Guo et al., 2004; Vlasenko et al., 2009). Most VOCs exhibit lower mixing ratios than in urban measurements (Liu et al., 2008; Leuchner and Rappenglück, 2010) and plumes, with the exception of acetone which was similar to measurements made downwind of Mexico City (de Gouw et al., 2009; Bon et al., 2011).

Alkanes typically were highest in concentration during the early morning hours when the PBLH was at a minimum, especially early in the campaign (5–7 June). Back trajectories and wind directions during these periods show the air usually approached the site from an area of well heads and other oil and gas infrastructure (Fig. S1). Aromatics showed similar enhancements during these periods. Other periods that exhibited enhanced aromatic mixing ratios corresponded to wind directions associated with other oil and gas operations (that likely have a different emissions profile) and with the small local airports. A distinct period of elevated biogenic influence (based on isoprene and monoterpenes) was observed during the few days leading up to and including the thunderstorm on 21 June. Back trajectories for 12:00 and 18:00 local time on these days indicate that air masses typically came from the southwest and not directly from DFW. It is assumed that these areas are more densely forested based on on-line satellite images. Concentrations of monoterpenes reached a campaign maximum after the thunderstorm on 6/21, which was nearly twice as large as the next highest concentration (Haase et al., 2011).

3.3. VOC PMF

The results from the EPA PMF 3.0 for the VOC data are shown in Figs. 3 and 4, with statistics presented in Table 3. The profiles for each source type indicate how each species is distributed between different inferred sources (Fig. 3). For example, the ethane percentages across the six factors would add up to 100% if all ethane mass could be attributed.

The Natural Gas factor contained most of the short chain alkanes such as ethane and propane (Buzcu and Fraser, 2006; Brown et al., 2007) and was higher in concentration at night when the PBLH was lower (Fig. 4). This was consistent with emissions from oil and gas development infrastructure surrounding the monitoring site. A factor containing most of the C_4 through C_7 alkanes was thought to be fugitive emissions of gasoline from fuel stations and/or product

Table 1
Statistics for hourly averages of measured CO, BC, SO_2, NO_x, O_3, and OA. Min represents the minimum observed value, and max represents the maximum observed value. 95th indicates the 95th percentile value.

Statistics	Carbon monoxide (ppm)	Black carbon (μg m^{-3})	Sulfur dioxide (ppb)	NO_x (ppb)	Ozone (ppb)	Organic aerosols (μg m^{-3})
Mean	0.15	0.5	0.4	3.7	40.8	4.6
Median	0.13	0.4	0.2	2.1	39.7	3.7
Min	0.05	0.1	BDL	0.2	5.05	0.7
Max	0.86	1.9	4.9	30.6	106.1	16.7
95th	0.24	1.2	1.1	11.4	74.3	9.2

Table 2
Statistics defined in Table 1 for key VOCs measured with an autoGC and a PTR-MS calculated using hourly averages. Units are ppb.

Statistics	Ethane	Propane	Toluene	Benzene	C_8 aromatics	C_9 aromatics	Isoprene	Mono-terpenes	Acetone	MVK & methacrolein	Methyl ethyl ketone	Methyl glyoxal
Mean	5.5	2.2	0.13	0.10	0.07	0.05	0.29	0.15	3.2	0.70	0.30	0.38
Median	3.6	1.5	0.09	0.08	0.04	0.03	0.25	0.12	3.0	0.61	0.24	0.34
Min	0.8	0.2	0.04	0.03	0.01	0.01	0.06	0.04	1.2	0.09	0.09	0.12
Max	48.7	16.0	0.80	0.43	0.57	0.47	1.13	1.36	6.7	2.61	0.85	0.92
95th	17.7	7.4	0.35	0.22	0.25	0.18	0.64	0.37	5.7	1.57	0.59	0.75

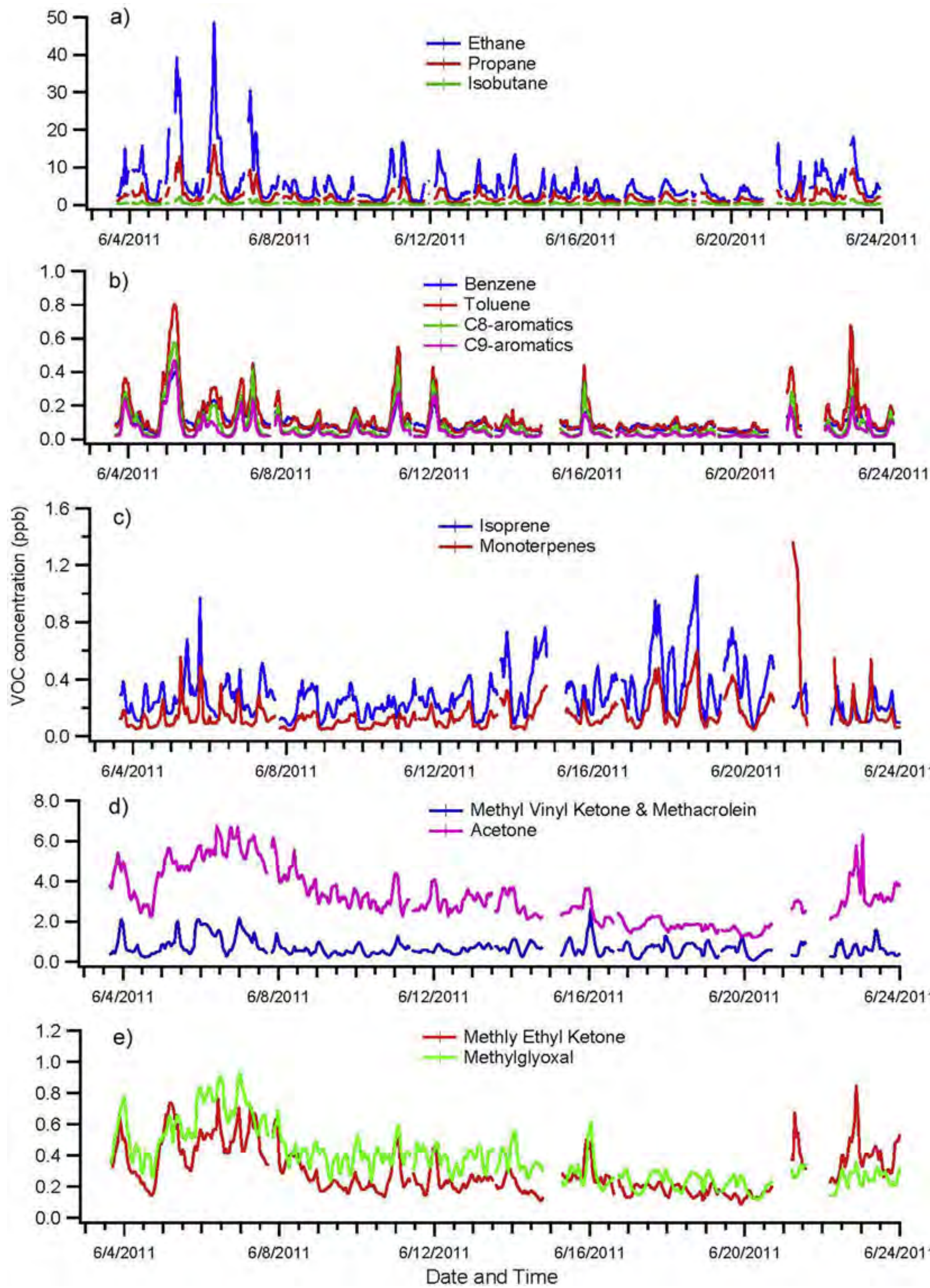

Fig. 2. Time series of VOC concentrations during the campaign. a.) Light alkanes; b.) Aromatics; c.) Biogenic VOCs; d.) Oxygenated VOCs; e.) Additional oxygenated VOCs.

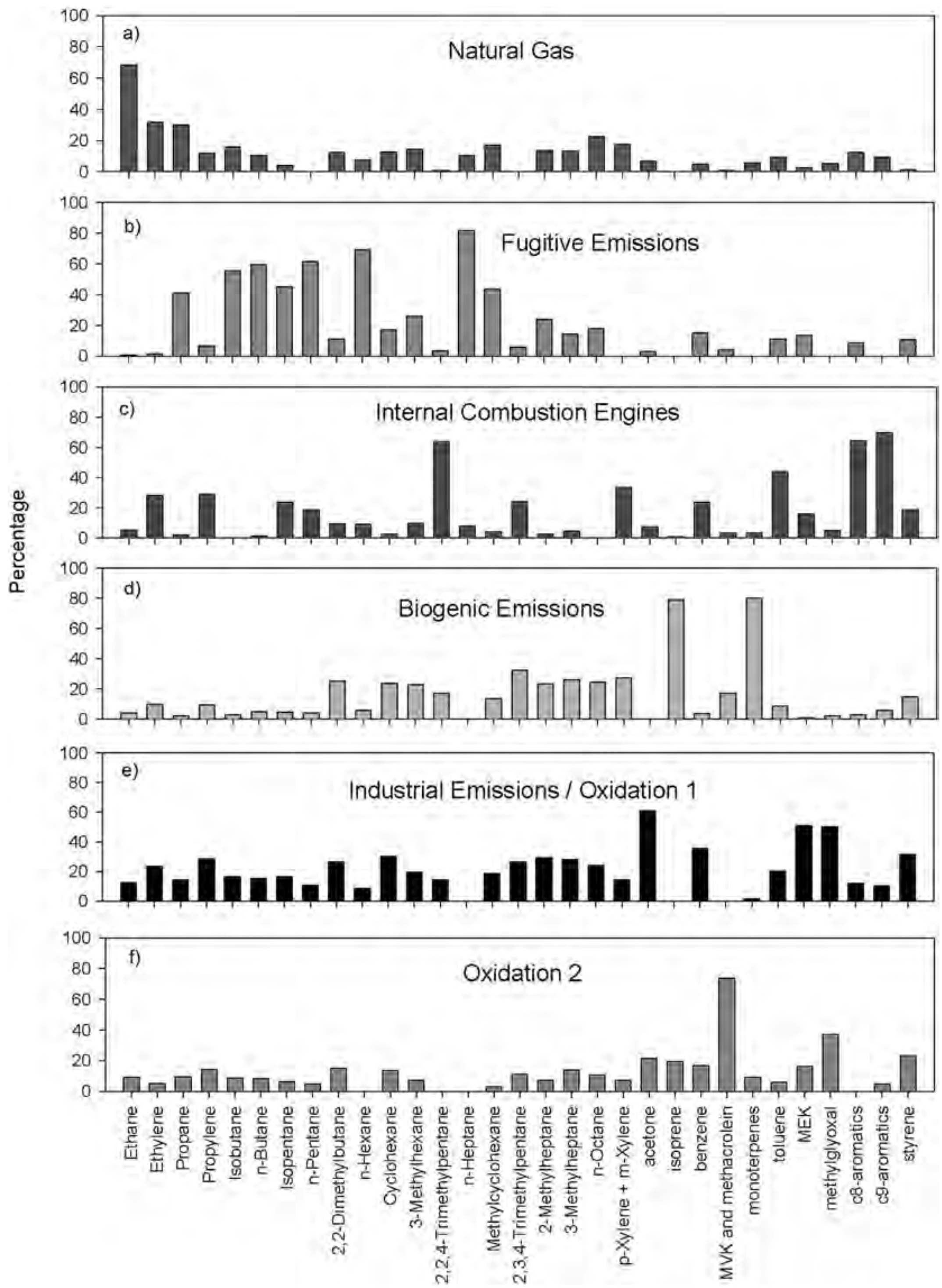

Fig. 3. PMF profiles for VOCs during the campaign. a.) Natural Gas; b.) Fugitive Emissions; c.) Internal Combustion Engines; d.) Biogenic Emissions; e.) Industrial Emissions/ Oxidation 1; f.) Oxidation 2.

from oil and gas development infrastructure (Fujita et al., 1994; Buzcu and Fraser, 2006; Brown et al., 2007; USEPA, 2014). Furthermore, the concentration of this Fugitive Emissions factor was higher overnight when the PBLH was lower, consistent with local, continuously emitting sources. The Fugitive Emissions time series is highly correlated with the Natural Gas factor (Fig. S3).

The assignment of the Internal Combustion Engine factor was based on apportionment of aromatics and 2,2,4- trimethylpentane, which are important components of gasoline (USEPA, 2000). This factor peaked both overnight (boundary layer) and at times shifted slightly from traditional rush hour periods (related to transport time from DFW).

The Biogenic factor contained most of the isoprene and monoterpenes (Fig. 3). As a result, the Biogenic factor shows characteristics that correspond to the isoprene and monoterpene time series (Figs. 2 and 4). The diurnal profile of the Biogenic factor is

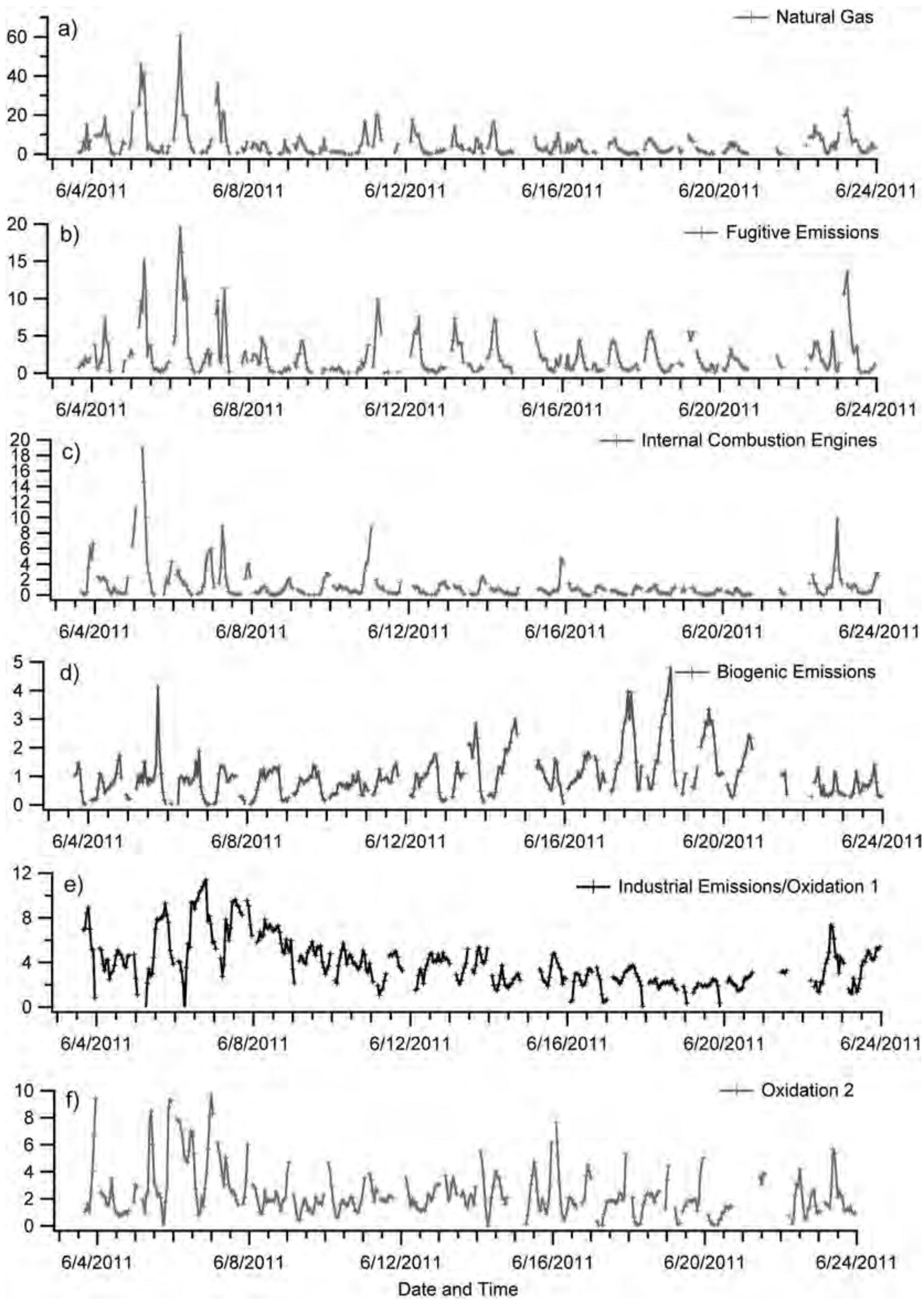

Fig. 4. Time series of PMF factors for VOCs during the campaign. a.) Natural Gas; b.) Fugitive Emissions; c.) Internal Combustion Engines; d.) Biogenic Emissions; e.) Industrial Emissions/Oxidation 1; f.) Oxidation 2. Y-axis units are ppb.

consistent with plant emissions related to photosynthesis and affected by temperature (Fig. 1 and Fig. S4). A small fraction of the longer chain alkanes and aromatics measured by the auto-GC are allocated to this factor. This may be because biogenic compounds are always present in polluted air or due to biogenic emissions of non-terpenoid compounds (White et al., 2009).

The Industrial Emissions/Oxidation 1 factor represents a combination of primary industrial VOCs mixed with oxidized VOCs. This factor included significant loadings of acetone, methyl ethyl ketone (MEK), methylglyoxal, benzene, styrene and several of the alkanes and alkenes. A weak diurnal variation is seen in the Industrial Emissions/Oxidation 1 factor, with lowest concentrations during

Table 3
Statistics defined in Table 1 for the VOC and OA factors calculated using hourly averages.

Statistics	VOC factors (ppb)						OA factors ($\mu g\ m^{-3}$)		
	Natural Gas	Fugitive emissions	Internal combustion engines	Biogenic	Industrial emissions/oxidation 1	Oxidation 2	HOA	SV-OOA	LV-OOA
Mean	5.4	2.3	1.2	1.0	3.8	2.4	0.5	2.5	1.7
Median	2.5	1.1	0.7	0.8	3.3	2.0	0.3	1.6	1.4
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	61.0	19.6	19.0	4.8	11.4	9.7	3.2	9.8	4.6
95th	21.1	9.9	4.3	2.6	8.8	6.1	1.4	6.8	3.7

local morning hours. Acetone and MEK both have primary and secondary sources (de Gouw et al., 2005; Vlasenko et al., 2009), while methyl glyoxal is an oxidation product of both anthropogenic and biogenic VOCs (Nishino et al., 2010; Galloway et al., 2011; Henry et al., 2011). The trend is consistent with emissions from DFW that are being oxidized during transport to the site.

The Oxidation 2 factor was found to have significant loadings of the isoprene-oxidation products methyl vinyl ketone (MVK), methacrolein (MACR), and methylglyoxal (Pierotti et al., 1990; Galloway et al., 2011). Because of the short lifetimes of isoprene under highly-photochemically active scenarios, it is believed that Oxidation 2 represents rapid oxidative processing of local biogenic emissions. The diurnal trend is bimodal in nature, exhibiting a smaller daytime mode which peaks around midday consistent with a secondary formation process, and a larger nighttime mode caused by PBLH dynamics (Fig. S4) (Montzka et al., 1993).

3.4. Reactivity calculations

The relative potential impacts of VOC sources on O_3 formation was explored by calculating the combined OH reactivity of each source profile using the methodology described previously (Fig. 5). The biogenic factor contributed the most OH reactivity (42%). Oxidation 2, thought to be related to biogenic oxidation, was the next largest contributor (28%). These two factors indicate the predominance of biogenic activity with regard to potential local O_3 formation (on average, 70%). The next most important factor was that for Industrial Emissions/Oxidation 1 (10%), which is related to outflow from DFW. In contrast, Internal Combustion Engine emissions originated from both DFW and the oil and gas development, contributed an average of 7% of the OH reactivity. Natural Gas and Fugitive Emissions are thought to be related predominantly to oil and gas operations. Together, they contributed the final 13% of the average OH reactivity. Although a smaller percentage of the total OH reactivity, they might incrementally increase O_3 concentrations within the DFW monitoring domain. The relative contributions between sources varied diurnally but were generally consistent throughout the course of the 3 week study period (Fig. 5).

3.5. HR-ToF-AMS PMF

The PMF model applied to the HR-ToF-AMS OA measurements best resolved three factors robustly (Fig. 6 and Fig. S5; Table 3). Factor 1 is attributed to HOA due to the large contribution of C_xH_y fragments even at large m/z and only a modest contribution from CO_2^+ ($m/z = 44$). Factors 2 and 3 have much more significant contributions from CO_2^+ and much less significant contributions from the various C_xH_y fragments. At first glance there appears to be little difference between these two OOA factors, although closer inspection reveals that the SV-OOA has a smaller signal ratio for m/z 44 to m/z 43 ($C_3H_7^+$) and larger contributions from fragments at larger m/z values compared to the LV-OOA.

Time series and diurnal profiles of the OA factors show both similarities and differences to the VOC factors (Fig. 6 and Fig. S6). The HOA time series show characteristics very similar to those of the Internal Combustion Engine factor (Fig. 4 and Fig. S6). A regression of the HOA and Internal Combustion Engine factors reveals a modest correlation (Fig. 7, top panel), which is supported by a positive correlation between HOA and CO (Fig. S7, top panel). These correlations indicate that HOA is in part due to mobile sources, likely due to emission of lubricating oil rather than unburned fuel (Schauer et al., 1999). Stationary engines are used to drive compressors in the oil and gas distribution lines on the Barnett Shale (Armendariz, 2009). No correlation was observed between HOA and other primary VOCs such as those that would be emitted from these engines, indicating the probable lack of significant OA emissions associated with these VOC emission processes.

The SV-OOA time series shows increased concentrations at the start and end of the study (Fig. 6), consistent with elevated nocturnal precursor VOCs (such as the aromatics shown in Fig. 2b), oxidized VOCs, and HOA during these periods (Figs. 2 and 6). However, the concentrations of SV-OOA decrease after 22:00 (Fig. S6). This behavior is also apparent in acetone, MEK, methyl glyoxal and BC (Fig. 2), implying that SV-OOA is not being generated locally at night at a rate in excess of its loss rate. The trends in the median concentrations in the diurnal profile of SV-OOA are consistent with the daytime formation of an oxidized species upwind that is then delayed by a few hours in arriving at the site. Similarities in the features of the SV-OOA and oxidized VOCs time series also suggests that these species may be chemically related during these periods of the study.

Elevated concentrations of SV-OOA are observed during the middle of the study, a trend which is not reflected in the gaseous or BC measurements except isoprene. It is possible the SV-OOA during this period is driven more strongly by oxidation of this biogenic VOC. The trend also is observed in LV-OOA. Similarities between the OOA factor trends, although vague in some instances, are observed in the latter part of the campaign (12–24 June). This suggests that the OOA factors may be chemically related during the second half of the study, but not the first. The diurnal profile of LV-OOA shows increased concentrations towards the late afternoon and evening hours, similar to SV-OOA (Fig. S6). This trend is consistent with formation of LV-OOA, potentially from aging of SV-OOA during transport from further upwind.

The SV-OOA factor was correlated with the sum of the Industrial Emissions/Oxidation 1 and Oxidation 2 VOC factors despite the mixed biogenic/industrial influence on the oxidation signals (Fig. S7, bottom panel), particularly after measurements following the meteorological transition on 6/21 were excluded (Fig. 7, bottom panel). It is possible that SV-OOA and the oxidized VOC factors correlated reasonably well because these factors may be separated by only a few steps if considering multi-generational oxidation processes (Jimenez et al., 2009). That is, the VOC Oxidation factors include first- or second-generation oxidation products such as acetone, MVK, MACR, etc. The presence of first and second generation oxidation products in the VOC oxidation factors suggests they

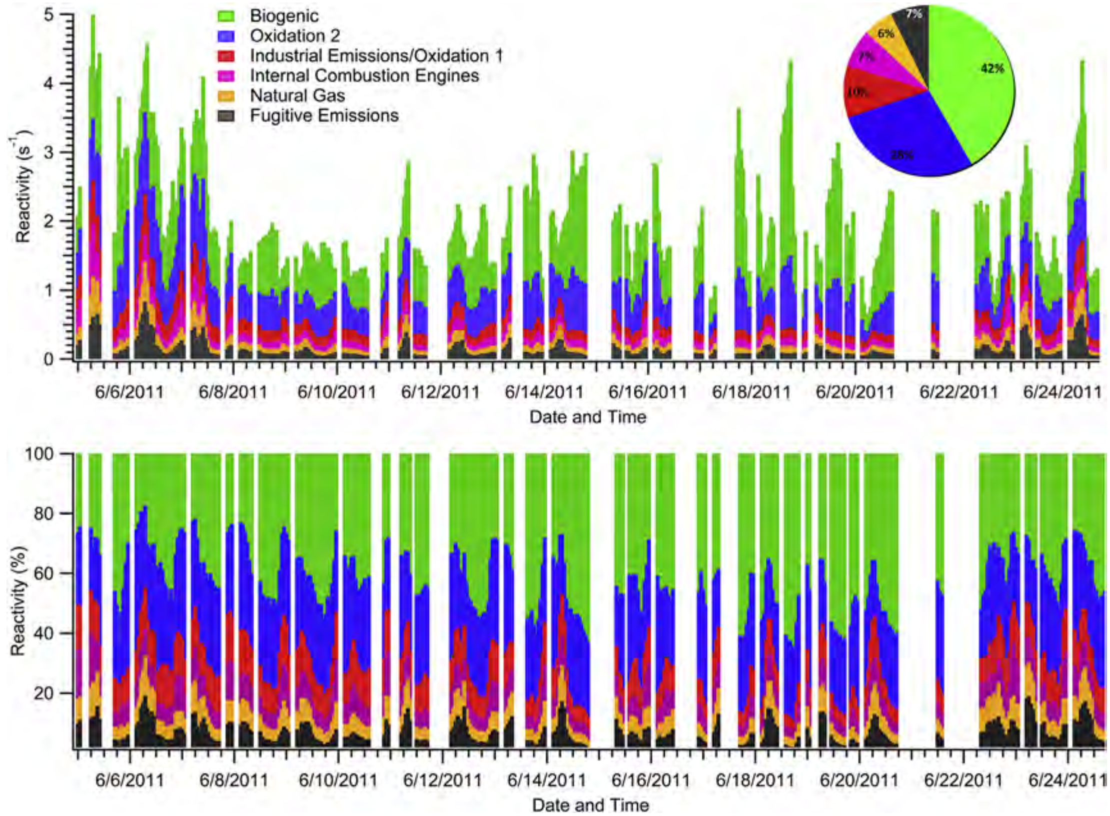

Fig. 5. Reactivity attributed to specific VOC factors during the campaign expressed in absolute values (top panel) and relative fractions (bottom panel); the inset pie chart shows the average contribution of each factor across the campaign.

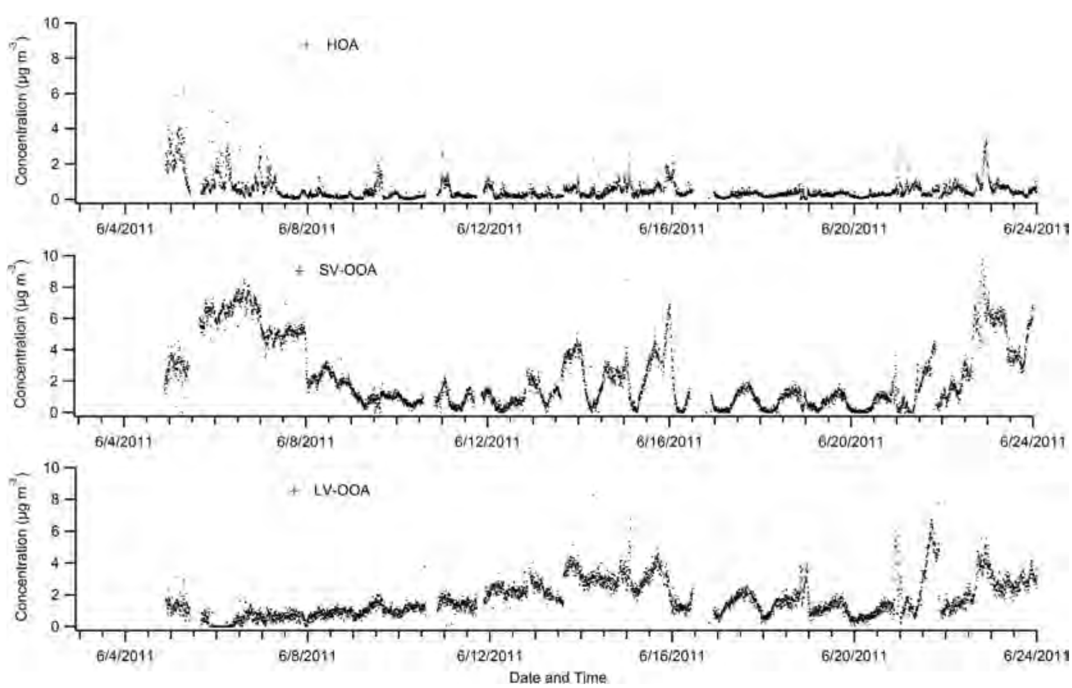

Fig. 6. PMF time series for OA types. Measurements are presented as 5 min averages. Top = HOA; middle = SV-OOA; bottom = LV-OOA.

were formed or emitted in the DFW area. The correlation between SV-OOA and the VOC oxidation factors suggests that much of this component was formed locally during the day.

Correlation between the LV-OOA and the oxidized VOC factors (Fig. 8) revealed two distinct relationships, with the shift between the two occurring on 6/9 due to a meteorological transition (Fig. 1; see wind direction, wind speed, barometric pressure). The division between the data sets occurs within a few days of the change in

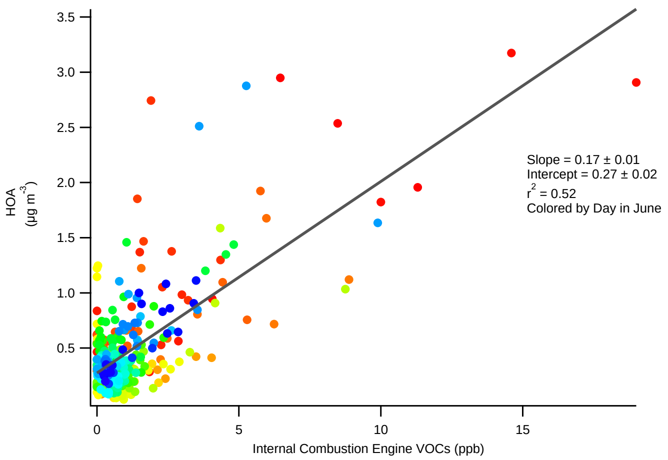

Fig. 7. Regressions between HOA and VOC from Internal Combustions Engines (top panel) and between SV-OOA and the sum of oxidized VOC factors with data for certain dates excluded as discussed in the text (bottom panel).

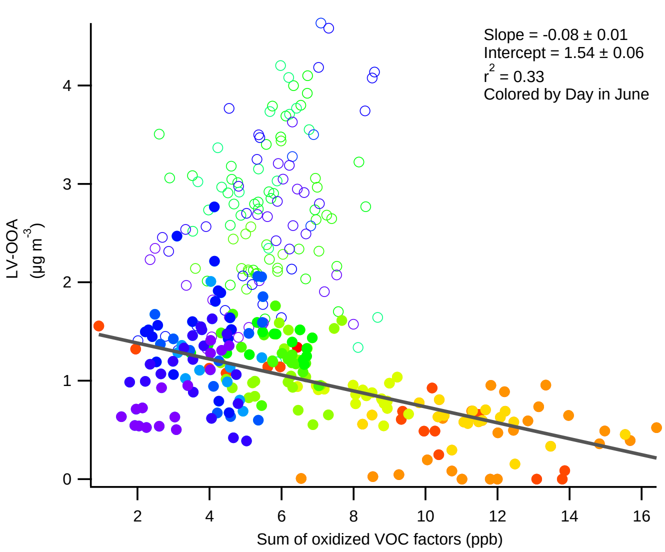

Fig. 8. Regression between LV-OOA and the sum of oxidized VOC factors. The panel includes all data in the study but only the filled circles are fitted. Open circles are measurements made before meteorological transitions on 6/9 and after 6/21. Data markers are colored by day in June.

relationship observed between SV-OOA and LV-OOA in Fig. 6. Little or no correlation is observed between LV-OOA and the oxidized VOCs at the start of the campaign (open circles). Measurements of LV-OOA after 6/9 and before 6/21 demonstrate a modest inverse correlation with the oxidized VOC factors. This relationship is reasonable for more aged OA. They are further removed from the parent VOCs and the measured oxidized VOCs along the oxidation pathway of organic compounds. The inverse nature of the relationship may imply gas-particle partitioning of oxidized VOCs to form OOA.

4. Conclusions

The objective of this study was to gain insight into the relative influences on air quality of VOC sources in the oil and gas development on the Barnett Shale and in the greater DFW metroplex. The VOC apportionment of autoGC and PTR-MS measurements revealed six factors and seven sources of VOCs (five primary and two secondary), with one of the factors being a mixture of a primary and secondary sources. Reactivity calculations showed that the majority of OH reactivity was contributed by biogenic sources and oxidized biogenic VOCs. However, enough OH reactivity was calculated for factors related to the oil and gas development that they could incrementally increase O_3. The OA mass was apportioned into HOA, SV-OOA, and LV-OOA. The HOA showed modest correlations with VOCs associated with internal combustion engines and CO, suggesting that about half of the observed HOA came from this source. The SV-OOA correlated well with the oxidized VOCs until a transition in meteorology occurred towards the end of the study, suggesting that much of SV-OOA originated from oxidized VOCs in the local urban outflow. The LV-OOA exhibited an inverse correlation with the oxidized VOCs for part of the study but did not correlate well outside of this period, suggesting in general that LV-OOA represents a well-aged aerosol. Relationships suggested that most of the OA mass originated from sources unrelated to oil and gas development.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.08.073.

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Review article

Unconventional oil and gas development and health outcomes: A scoping review of the epidemiological research

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ABSTRACT

Background: Hydraulic fracturing together with directional and horizontal well drilling (unconventional oil and gas (UOG) development) has increased substantially over the last decade. UOG development is a complex process presenting many potential environmental health hazards, raising serious public concern.
Aim: To conduct a scoping review to assess what is known about the human health outcomes associated with exposure to UOG development.
Methods: We performed a literature search in MEDLINE and SCOPUS for epidemiological studies of exposure to UOG development and verified human health outcomes published through August 15, 2019. For each eligible study we extracted data on the study design, study population, health outcomes, exposure assessment approach, statistical methodology, and potential confounders. We reviewed the articles based on categories of health outcomes.
Results: We identified 806 published articles, most of which were published during the last three years. After screening, 40 peer-reviewed articles were selected for full text evaluation and of these, 29 articles met our inclusion criteria. Studies evaluated pregnancy outcomes, cancer incidence, hospitalizations, asthma exacerbations, sexually transmitted diseases, and injuries or mortality from traffic accidents. Our review found that 25 of the 29 studies reported at least one statistically significant association between the UOG exposure metric and an adverse health outcome. The most commonly studied endpoint was adverse birth outcomes, particularly preterm deliveries and low birth weight. Few studies evaluated the mediating pathways that may underpin these associations, highlighting a clear need for research on the potential exposure pathways and mechanisms underlying observed relationships.
Conclusions: This review highlights the heterogeneity among studies with respect to study design, outcome of interest, and exposure assessment methodology. Though replication in other populations is important, current research points to a growing body of evidence of health problems in communities living near UOG sites.

1. Background

Unconventional oil and gas (UOG) development extracts oil and gas directly from source rock formations, which are fine-grained rock layers where oil and gas are formed, or from tight sand formations just above these source rocks; both types of formations have low permeability and are characterized by very low hydraulic conductivity. Fossil fuels extracted from these low-porous formations are referred to as shale-oil or shale-gas, tight gas, coal seam gas or coal bed methane (National Energy Board and Canadian Electronic Library, 2012; U.S.

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List of abbreviations

AMI	acute myocardial infarction
ALL	acute lymphocytic leukemia
CHD	congenital heart defects
CI	confidence intervals
CSG	coal seam gas
COPD	chronic obstructive pulmonary disease
CM	congenital malformations
DAGs	directed acyclic graphs
Fetal health index	a measure that incorporates a number of health outcomes in order to reduce the number of statistical tests - birth weight, LBW, PTD, congenital malformation
HIA	health impact assessment
ICD-9	International Classification of Diseases, Ninth Revision
IDW	inverse distance weight or inverse-distance squared weight methods
LBW	birthweight smaller than 2500 g
NHL	non-Hodgkin lymphoma
NTD	neural tube defects
PTD	preterm deliveries - births before 37 completed weeks of gestation
Extremely PTD	births before 28 completed weeks of gestation
Very PTD	births after 27 and before 32 completed weeks of gestation and
Moderately PTD	births after 31 and before 37 completed weeks of gestation
SGA	small-for-gestational age - birth weight for gestational age and sex smaller then 10th percentile.
TLBW	term LBW- birthweight smaller than 2500 g and 37 completed weeks of gestation
O&G	combined conventional and unconventional oil and gas
OR	Odds Ratio
$PM_{2.5}$	fine particles with a diameter of 2.5 μm or less
PM_{10}	particles with a diameter of 10 μm or less
SIRs	Standardized Incidence Ratios
STD	sexually transmitted Disease
UOG	unconventional oil and gas
URI	upper respiratory infections

Environmental Protection Agency, 2016; Werner et al., 2015). This process contrasts with conventional oil and oil and gas production which involves the extraction of oil and gas from more accessible, permeable reservoir rocks that collect migrating hydrocarbons.

UOG development utilizes intensive spatial-clustering of wells, directional drilling, and high-volume hydraulic fracturing. These techniques increase production efficiency from the low-permeable source rocks, expand the accessible region of the target geological configuration, and enhance cost-effectiveness through a tighter spatial-clustering of wells (Ewen et al., 2012; U.S. Environmental Protection Agency, 2016). Although hydraulic fracturing and other stimulation methods such as acid stimulation have been used in the drilling industry for the water and conventional oil and gas sectors for more than 60 years (Hays et al., 2015), the combination of intensive directional drilling and high-volume hydraulic fracturing has only occurred since 2005 (Fukui et al., 2017).

UOG development is a complex, multi-stage process that follows similar overall phases, although the specific steps and their durations vary by geological formations, wells, and operators. Initially, well preparation occurs (lasting about 30 days), during which approximately 0.1–0.2 ha (1000–2000 square meters) are cleared and materials are transported to the site. Next, the well is drilled vertically to the desired depth (~0–2 weeks) and then horizontally or directionally into the source formation (~0–6 weeks). The hydraulic fracturing or “fracking” (~1 week), which is the stimulation of the flow of natural gas or oil through injection of large volumes of pressurized fracturing fluids (a mix of water, sand, and chemical additives), creating and reopening cracks or fissures in the deep-rock formations to release the trapped oil or gas (U.S. Environmental Protection Agency, 2016). Gas or oil production begins after the stage of stimulation (Graham et al., 2015).

UOG development has revolutionized the global energy market, leading to reduced global prices of oil and gas (Fukui et al., 2017). While UOG development may confer economic benefits such as national economic growth (increase in GDP), increased number of new jobs, increased state tax revenues, and energy independence (The Congressional Budget Office CBO, 2014; Erbach, 2014), this process also has the potential to adversely affect the environment and human health in numerous ways (Hays and Shonkoff, 2016a; Kibble et al., 2014; Martens and Zucker, 2014; Werner et al., 2015). Although both conventional and unconventional oil and gas development can release similar hazardous pollutants compared with conventional (Czolowski et al., 2017), UOG development is highly intensive in water consumption (100–1000 times greater) and is characterized by higher well pressures and a higher well density (Jackson et al., 2014). In addition, UOG processes create large amounts of waste water (some of which is being transferred out of state), higher traffic volumes, and high use of diesel engines that can emit pollutants to the environment (air, soil and water), result in high noise levels, induce earthquakes, have negative effects on livestock, can cause changes in the population social characteristics and damage biological diversity (Adgate et al., 2014; Hays et al., 2017).

Several prior scoping and systematic literature reviews summarized the potential effect of UOG development on the environment (mainly water and air quality) or on psychological and physiological health (Balise et al., 2016; Gorski et al., 2019; Hays and Shonkoff, 2016a; Hirsch et al., 2018; Saunders et al., 2018; Stacy, 2017; Wright and Muma, 2018). These reviews included qualitative studies, risk assessments, toxicological studies, environmental monitoring studies, and epidemiological studies of self-reported and clinician-diagnosed health outcomes. The most recent systematic literature review focusing on epidemiological assessments of UOG exposure included articles published through October 2018 (Bamber et al., 2019). Our review expands upon prior publications by including studies published through August 15, 2019 and by assessing less commonly included health endpoints such as injuries and mortality from vehicle accidents and increases in sexually transmitted infections; these outcomes may have arisen not from the direct effect of UOG on the environment (air and water), but from increased vehicle traffic and working populations into rural areas. Furthermore, our exclusive focus on epidemiologic analyses (i.e., exclusion of risk assessments and qualitative studies) enabled a deeper assessment of study methods and a detailed synthesis of results for five selected health endpoints.

The motivation to conduct this study was to provide evidence on the health outcomes of UOG development and production processes for an interdisciplinary research team that serves as an advisory committee to the Israeli Ministry of Energy on UOG processes. In Israel, to date, there has been no UOG development. In recent years, several discussions have taken place in the Israeli Parliament (Knesset) and government ministries on this issue. We assessed epidemiologic studies published worldwide to compile available health-based evidence for use by decision makers in Israel and elsewhere.

2. Methods

A scoping review was conducted to identify all studies that examined direct associations between UOG development and human health outcomes as well as to identify the existing gaps in the knowledge. A scoping review allows for the inclusion of studies with different methodological designs. Unlike systematic reviews, scoping reviews do not assess the quality of the included studies, but rather address a broader issue based on the current literature (Colquhoun et al., 2014). We followed the first five stages of scoping review as defined by Arksey and O'Malley(2005): 1) research question was identified, 2) relevant studies for inclusion were identified, 3) studies were selected, 4) the data was charted, and 5) results were collated, reported and summarized. For the last stage we used the enhanced definition by Levac et al. (2010) and we discuss the findings as they relate to the study purpose and implications for future research, practice and policy.

The framework for our approach is presented in Fig. 1. Our broad research question was: "What is known from the existing literature about the human health outcomes associated with living near UOG wells?" The bibliographic search was conducted using MEDLINE (National Library of Medicine) and SCOPUS search engines with the following keywords related to unconventional oil and gas combined with keywords related to health: ("unconventional gas" OR "unconventional oil" OR "shale gas" OR "tight gas" OR "coal seam gas" OR "natural gas") AND ("Health" OR "epidemiological study" OR "physiological" OR "psychological" OR "hospitalization" OR "Asthma" OR "Injury" OR "mortality" OR "Cancer" OR "morbidity" OR "Adverse pregnancy outcomes" OR "Birth" OR "congenital Malformation" OR "birth defects" OR "birth weight" OR "low birth weight" OR "preterm birth" OR "premature birth" OR "preterm delivery" OR "small for gestational age" OR "LBW" OR "PTB" OR "PTD" OR "SGA"). The search was limited to the English language and to studies on humans. The country where the study had been conducted was not an inclusion criterion. The last search was conducted on August 15, 2019. Initial screening of the articles was conducted based on the information available in the titles and abstracts. Each article passing this initial screening stage was reviewed to decide whether it was eligible for inclusion. References of the relevant articles were also checked to find additional articles fitting the inclusion criteria.

2.1. Study selection

We identified 806 articles in MEDLINE, SCOPUS and other sources (Fig. 1). After screening the title and abstracts and checking for duplicates, 40 articles were chosen for full text evaluation. After full text evaluation, we excluded studies with self-reported symptoms not verified by clinicians due to the subjective nature of such data, which may cause bias (Casey et al., 2018; Elliott et al., 2018; Ferrar et al., 2013; Rabinowitz et al., 2014; Saberi, 2013; Saberi et al., 2014; Shamasunder et al., 2018; Steinzor et al., 2013, 2012; Tustin et al., 2016; Weinberger et al., 2017). Furthermore, studies that evaluated car accidents without health outcomes (Amber Brooke Trueblood and Garett Sansom, 2015) following UOG development activity were also excluded.

The selection criteria for the studies were as follows: a) peer-reviewed and published in academic journals; b) original research articles; c) adhering to any type of epidemiological study design (ecological, time-series, cross-sectional, case-control, nested case-controls, cohort, and panel studies – "differences in differences"); d) the exposure to UOG development or exposure to UOG and conventional oil and gas development combined was evaluated as a separate variable within the analysis; and e) studies that evaluated health outcomes (psychological and physiological) diagnosed by clinician, based on morbidity and mortality databases, rather than self-reported symptoms assessed by questioners with no clinical verification.

Twenty nine studies met our criteria and were eligible for inclusion in our review (Beleche and Cintina, 2018; Blair et al., 2018; Busby and Mangano, 2017; Casey et al., 2019, 2015; Currie et al., 2017; Denham et al., 2019; Deziel et al., 2018; Finkel, 2016; Fryzek et al., 2013; Graham et al., 2015; Hill, 2018; Janitz et al., 2019; Jemielita et al., 2015; Komarek and Cseh, 2017; Ma, 2016; McKenzie et al., 2019b, 2019a; 2017, 2014; Peng et al., 2018; Rasmussen et al., 2016; Stacy et al., 2015; Walker Whitworth et al., 2018; Werner et al., 2017, 2018; 2016; Whitworth et al., 2017; Willis et al., 2018). For these studies, we extracted the following information: author, year of publication, country, sample size and study population, study design, outcome measured, approach used to evaluate the exposure, statistical approach,

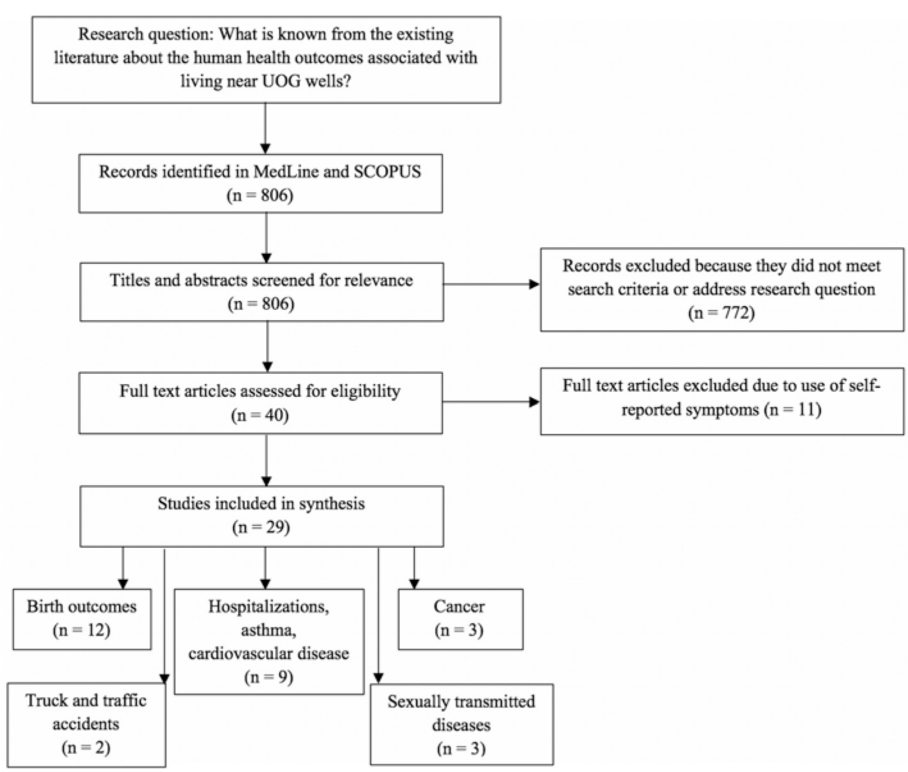

Fig. 1. Flow chart of the scoping review showing inclusion and exclusion strategy.

Table 1
Main characteristics and results of the studies on adverse pregnancy outcomes.

Researchers	Location	Population, outcome and study design	Exposure evaluation approach	Statistical approach and Exposure levels	Confounders	Main findings
McKenzie et al., (2014) (McKenzie et al., 2014)	Rural Colorado (USA)	**Population:** 124,842 births born between 1996 and 2009. **Outcomes**: Congenital malformation (CM) (Oral clefts, neural tube defects [NTDs], congenital heart defects [CHDs]), preterm delivery [PTD], term low birth weight [TLBW], term birth weight. -**Retrospective cohort study**	- Inverse distance-weighted well counts within 10-mile radius	The tertiles of exposure were compared to the zero wells category. T1: 1–3.62 wells/mile; T2: 3.63–125 wells/mile; T3: 126–1400 wells/mile	Maternal age, ethnicity, smoking, alcohol use, education, and elevation of residence, as well as infant parity and sex.	Exposure to highest tertile compared to the reference category: -CHDs ↑ (OR:1.3, 95% CI: 1.2, 1.5). -NTD ↑ (OR:2.0; 95% CI: 1.0, 3.9). -Oral clefts ↘ (OR:0.82; 95% CI: 0.55, 1.2) -PTD ↓ (OR:0.91; 95% CI: 0.85, 1.0) -TLBW ↓ (OR:0.90; 95% CI: 0.80, 1.0) - Mean term birth weight ↑ (22 gr, 95% CI:15, 29)
Stacy et al., (2015) (Stacy et al., 2015)	Southwest Pennsylvania (USA)	**Population:** 15,451 live births born between 2007 and 2010. **Outcomes**: Birth weight, small for gestational age [SGA], PTD -**Retrospective cohort study**	- Inverse distance-weighted sum of natural gas wells within 10-mile radius (not just UOG)	Quartiles of exposure were compared to the lowest quartile. Q1: 0–0.86 wells/mile Q2: 0.87–2.59 wells/mile Q3: 2.6–5.99 wells/mile Q4: ≥6.00 wells/mile.	Maternal age, education, pre-pregnancy weight, gestational age (for birth weight), child gender, prenatal visits, smoking, gestational diabetes, WIC assistance (Women, Infants, and Children), race, and birth order.	Exposure to highest quartile compared to the lowest quartile: -SGA ↑ (OR: 1.34, 95% CI:1.10,1.63) -Mean birth weight ↓ (−21.8 gr, 95% CI: 40.2, −3.4) -PTD ↔
Ma, 2016 (Ma, 2016)	Pennsylvania (USA)	**Population:** 1,401,813 births born between 2003 and 2012. **Outcomes**: Structural birth defects (anencephaly, meningomyelocele/ spina bifida, cyanotic congenital heart disease, congenital diaphragmatic hernia, omphalocele, gastroschisis, limb reduction defect, cleft lip with or without cleft palate, cleft palate alone, or hypospadias), functional or developmental birth defect (Down syndrome, suspected chromosomal disorder). -**Semi-ecological**	-Counts of UOG wells per zip codes. -Density of UOG wells per zip code.	Zip code with UOG compared to zip codes without UOG. In addition, the trend in CM prevalence in areas with UOG wells was compared to zip codes without UOG wells. Level of exposure not reported. A Figure of the research area, with UOG wells as points on the map.	Maternal age at delivery, maternal highest education level, self-designated race, maternal pre-pregnancy body mass index category, primary payer for delivery, mother receiving WIC assistance (Women, Infants, and Children), maternal pre and during pregnancy diabetes status, maternal pre and during pregnancy hypertension status, smoking, and maternal infection during pregnancy status reported on birth registry. Models for zip codes with vs. without UOG include UOG density as a confounder.	Living in zip codes with UOG compared to zip codes without UOG: -Any birth defects prevalence ↑ (OR:1.22, 95% CI: 1.13, 1.32) -Structural birth defects prevalence ↑ (OR:1.21, 95% CI: 1.11, 1.32) -Functional or developmental birth defects prevalence ↑ (OR:0.93, 95% CI: 0.85, 1.01) Increase in UOG well density per square kilometer: -Any birth defects prevalence ↘ (OR:0.93, 95% CI: 0.85, 1.01) -Structural birth defects prevalence ↘ (OR:0.95, 95% CI: 0.86, 1.04) -Functional or developmental birth defects prevalence ↘ (OR:0.90, 95% CI: 0.76, 1.07)
Casey et al. 2016 (Casey et al., 2015)	Central and northeast Pennsylvania (USA)	**Population:** 10,946 singleton neonates in the Geisinger Health System, born between 2009 and 2012 **Outcomes**: Term birth weight, PTD, low 5-min Apgar score (< 7), SGA and high-risk Pregnancy. -**Retrospective cohort study**	-Inverse distance-squared activity metrics (pad development, drilling, hydraulic fracturing, production). z-transformed and summed to create a final metric of total UOG activity sum. Without specification of radius.	The mean (SD) and median (IQR) number of well counts within 12.4 miles of pregnant mothers: Q1: 6 (28), 0 (0–1) Q4: 124 (202), 8 (1–122). The quartiles of UOG activity index were compared to the lowest quartile: Q1: less than −0.44; Q2: −0.43 to −0.15, Q3: −0.14 to 0.18, Q4: > 0.18.	Child sex and gestational age; season of birth; maternal characteristics: age at delivery, race/ethnicity, primary care patient status, smoking, pre-pregnancy BMI, parity, number of antibiotic orders during pregnancy, receipt of medical assistance, delivery hospital, drinking water source, distance to nearest major road, mean residential greenness during pregnancy; and community socioeconomic deprivation	Exposure to the highest activity index quartile, compared to the lowest quartile: -PTD ↑ (OR: 1.4,95% CI: 1.0, 1.9) -High-risk Pregnancy ↑ (OR: 1.3, 95% CI: 1.1, 1.7). - Mean term birth weight ↓ (−31 g, 95% CI: −57, −5) -Low 5-min Apgar score (< 7) ↔ -SGA ↔

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Table 1 (*continued*)

Researchers	Location	Population, outcome and study design	Exposure evaluation approach	Statistical approach and Exposure levels	Confounders	Main findings
					quartile. Mother and community were treated as random effects.	
Whitworth et al., (2017) (Whitworth et al., 2017)	North Texas (USA)	**Population:** 158,894 singleton births or fetal death born between November 30, 2010–November 29, 2012 **Outcomes**: SGA, PTD, fetal deaths and mean birth weight. -**Retrospective cohort study**	Inverse square distance-weighted sum of active UOG wells within three radiuses: 0.5 mile, 2 miles, and 10 miles.	Tertiles of exposure were calculated and compared to zero wells -Urban-suburban area Median (IQR) of IDW sum: 0.5 miles: 31.4(13.4–70.1); 2 miles: 24(7.9–51.2); 10 miles: 19.2(1–63.6); Median(IQR) of active UOG wells, by tertiles: 0.5 miles: T1: 1(1–2); T2:4(3–5); T3: 7(5–10) 2 miles: T1: 7(3–13); T2:32 (23–42); T3: 54(39–75) 10 miles: T1: 10(1–67); T2:32(267–748); T3: 1190(923–148)	Maternal age at delivery, pre-pregnancy BMI, race/ethnicity, education, smoking, adequacy of prenatal care utilization, and infant sex. Census tract was treated as random effect.	Exposure to highest tertiles of UOG-activity compared to zero wells (**0.5 mile**): - PTD ↑ (OR: 1.14,95% CI: 1.03, 1.25) -SGA ↔ (OR: 1.01,95% CI: 0.96, 1.06) - Fetal deaths ↗ (OR: 1.27,95% CI: 0.82, 1.97) - Mean birth weight ↔ (−0.83 g, 95% CI: 12.24, 10.58) Exposure to highest tertiles of UOG-activity compared to zero wells (**2 miles**): - PTD ↑ (OR: 1.14,95% CI: 1.07, 1.22) -SGA ↘ (OR: 0.95,95% CI: 0.90, 1.00) - Fetal deaths ↗ (OR: 1.16,95% CI: 0.86, 1.58) - Mean birth weight ↘ (−6.68 g, 95% CI: 14.38, 1.02) Exposure to highest tertiles of UOG-activity compared to zero wells (**10 miles**): - PTD ↑ (OR: 1.15,95% CI: 1.08, 1.22) -SGA ↘ (OR: 0.96,95% CI: 0.92, 1.01) - Fetal deaths ↑ (OR: 1.34,95% CI: 1.04, 1.72) - Mean birth weight ↘ (−6.56 g, 95% CI: 13.68, 0.56)
Currie et al., (2017) (Currie et al., 2017)	Pennsylvania (USA)	**Population:** 1,125,748 live births, born between 2004 and 2013 **Outcomes**: birthweight, LBW, infant health index (combination of birth weight and indicators for LBW, PTD, the presence of any CM, and the presence of any other abnormal condition of the newborn). -**Retrospective cohort study and differences in differences**.	"Nearest neighbor"- vector based on nearest UOG well and if conception occurred after the spud date (equal to 1 for births "near" any well sites for which the spud date precedes conception and is equal to 0 otherwise).	Differences in differences approach and in addition, maternal (for sibling) and county fixed effect models were used. Living within 0.6 miles of a UOG site and 0.6 to 1.8 miles was compared to the reference group (mothers living within 1.8–9.3 miles from a UOG well site). Level of exposure was not reported. Figure of the research area, with UOG wells as points on the map.	Child gender, maternal race, maternal ethnicity, maternal age, education marital status, and child parity.	Introduction of UOG, comparing close (living **within 0.6 mile**) versus further away (living within 1.8–9.3 miles of a UOG well): -LBW ↑ (a significant 25% increase in the probability) -Mean term birth weight ↓ -Infant health index ↑
Busby and Mangano (2017) (Busby and Mangano, 2017)	Pennsylvania counties (USA)	**Population:** 98,941 Live births and 431 infant mortalities (0–28 days), between 2003 and 2010. **Outcome**: Infant mortalities. -**Ecological study**	Rate ratio (RRs: rate for the period 2007–2010/rate for the period 2003–2006) for the 10 most UOG drilled counties: combined for each county, combined for five north eastern	In Pennsylvania: During 2003–2006: 44 UOG wells. During 2007–2010: 2864 UOG wells.	-No adjustment	Rate during 2007–2010 compared to rate during 2003–2006: -Infant mortalities, in the 10 fracked counties ↑ (RRs: 1.29, 95% CI: 1.05, 1.55) -Infant mortalities, for the five

(*continued on next page*)

Table 1 (*continued*)

Researchers	Location	Population, outcome and study design	Exposure evaluation approach	Statistical approach and Exposure levels	Confounders	Main findings
			counties, combined for five south-western counties; for all Pennsylvania.			north east counties↑ (RRs: 1.66, 95% CI: 1.05, 2.51) -Infant mortalities, for the five south western counties↗ (RRs: 1.18, 95% CI: 0.95, 1.46). -Increased risk was associated with exposure to groundwater, expressed as the county ratio of water wells divided by the number of births.
Walker Whitworth et al., 2018 (Walker Whitworth et al., 2018)	Texas (USA)	**Population:** 80,257 singleton births born between November 30, 2010–November 29,2012. All PTD cases (13,549) and randomly selected term births matched by maternal age group and race/ethnicity (67,745 controls). **Outcomes**: PTD and extremely PTD, very PTD and moderately PTD. -**Nested case-control study** within the cohort describe in Whitworth et al. (Whitworth et al., 2017)	Inverse distance-squared activity metrics for drilling and production of UOG well counts within 0.5 mile radius. - By trimesters 1, 2, or 3, or the entire pregnancy	UOG drilling and production metrics were categorized by tertiles and births with zero UOG drilling and production wells within 0.5 mile of the residence, served as the referent group. Level of exposure-see Whitworth et al. (Whitworth et al., 2017).	Pre-pregnancy BMI, education, smoking during pregnancy, infant sex, previous poor pregnancy outcome, and the adequacy of prenatal care utilization Index. (parity and maternal residential distance to the nearest major roadway were non-significant, maternal age and race/ethnicity were not included due to the matching).	Exposure to the third tertile compared to zero of the UOG **drilling activity**: All PTD, all pregnancy ↑ (OR: 1.20, 95% CI: 1.06, 1.37) Extremely PTD, all pregnancy↑ (OR: 2.00, 95% CI: 1.23,3.24) Very PTD, all pregnancy↗ (OR: 0.97, 95% CI: 0.62,1.52) Moderately PTD, all pregnancy↑ (OR: 1.18, 95% CI: 1.03,1.36) **By trimesters**: All PTD, first trimester↑ (OR: 1.24, 95% CI: 1.03,1.49) All PTD, second trimester↑ (OR:1.21, 95% CI: 1.00,1.45) All PTD, third trimester↗ (OR:1.19, 95% CI: 0.89,1.60) Exposure to third tertile compared to zero of the UOG-**production activity**: All PTD, all pregnancy ↑ (OR: 1.15, 95% CI: 1.05, 1.26) Extremely PTD, all pregnancy↑(OR: 1.53, 95% CI: 1.03,2.27) Very PTD, all pregnancy↗ (OR:1.01, 95% CI: 0.74,1.39) Moderately PTD, all pregnancy↑ (OR:1.15, 95% CI: 1.04,1.27) **By trimesters:** All PTD, first trimester ↑ (OR: 1.18, 95% CI: 1.02,1.37) All PTD, second trimester↗ (OR: 1.14, 95% CI: 0.99,1.31) All PTD, third trimester↘ (OR:0.89, 95% CI: 0.72,1.10)
Hill (2018) (Hill, 2018)	Pennsylvania, (USA)	**Population:** 1,098,884 singleton births born between 2003 and 2010. **Outcomes**: LBW, PTD and term birth weight. Gestational age, 5 min Apgar score less than 8, CM, an infant health index and infant mortality (during the first year)	"Nearest neighbor"- vector, similar to Currie et al. but focused on those living within approximately 1.5 miles, and as a sensitivity analysis studied other radiuses.	2459 natural gas wells spudded between 2006 and 2010 Drilled UOG wells compared to UOG wells permits.	Race, education, age, marital status, WIC status, insurance type, previous risky pregnancy, whether the mother smoked during her pregnancy, month of birth, year of birth, and gender of the child.	**After and before** the drilling of UOG wells, among infants born to mothers living within 2.2 miles of at least one well site during pregnancy: LBW ↑ (by 24 percent) SGA ↑ (by 18 percent)

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Table 1 (*continued*)

Researchers	Location	Population, outcome and study design	Exposure evaluation approach	Statistical approach and Exposure levels	Confounders	Main findings
		-Retrospective cohort and differences in differences.				Mean term birth weight ↓ (by 49.6 g) Mean birth weight ↓ (by 46.6 g) Five minute Apgar score less than 8↑ (by 26 percent) Infant health index ↑ (by 0.026 standard deviations) PTD ↗ CM ↘ For each **additional UOG well** drilled prior to birth within 2.5 km: LBW ↑ (by 7 percent) PTD ↑ (by 3 percent) Mean term birth weight ↓ (by 5 g) SGA ↔ Mean birth weight ↔ Five minute Apgar score less than 8↔ CM ↔
Janitz et al., (2019) (Janitz et al., 2019)	Oklahoma, (USA)	**Population:** 476,600 singleton births born between 1997 and 2009. **Outcomes**: Major CM: NTDs (spina bifida and anencephaly) (N = 217); Oral clefts (cleft lip and cleft palate) (N = 603); CHD (common truncus/truncus arteriosus, transposition of the great arteries, double outlet right ventricle, Tetralogy of Fallot, single ventricle, pulmonary valve atresia and stenosis, tricuspid valve atresia and stenosis, Ebstein anomaly, hypoplastic left heart syndrome, coarctation of aorta, interrupted aortic arch, and total anomalous pulmonary venous connection) (N = 874). **- Retrospective cohort study**.	-Inverse distance-squared (IDW)*(O&G) method of actively producing wells during the month of birth, within three radiuses of the maternal residence at delivery: 2 miles, 5 miles, and 10 miles. Natural gas well was classified as actively producing, if production was reported during at least one month in a given year.	Modified Poisson regression with robust error variance was used to calculate the prevalence proportion ratios (PPR). The IDW summed well counts at the 2-mile buffer were categorized to tertiles and compared to the zero wells category: T1: 0.25–1.88 wells; T2: > 1.88–9.00 wells; T3: > 9.00–47,679.13 wells. A total of 417,110 unique producing natural gas wells in Oklahoma over the study time period.	Using DAG, the researchers only adjust for maternal education.	Exposure to **highest tertile compared to the zero** reference category, at the 2-mile buffer: -NTD ↗ (PPR: 1.20, 95% CI: 0.82, 1.75). -Oral clefts ↔ (PPR: 1.03 95% CI:0.82, 1.29) -CHD ↘ (PPR: 0.91 95% CI: 0.75, 1.11). Exposure to **any natural gas activity compared to none**, at the 2-mile buffer: CHD: Common truncus ↗ (PPR: 1.15, 95% CI: 0.64, 2.06). Transposition of the great arteries ↗ (PPR: 1.15, 95% CI: 0.80, 1.65) Double outlet right ventricle ↘ (PPR: 0.77, 95% CI: 0.38, 1.57) Single ventricle↔ (PPR: 1.02, 95% CI: 0.63, 1.66) Pulmonary valve atresia and stenosis↗ (PPR: 1.45, 95% CI: 0.82, 2.55) Tricuspid valve atresia and stenosis ↗ (PPR: 1.32, 95% CI: 0.66, 2.63) Ebstein anomaly↘ (PPR: 0.95, 95% CI: 0.45, 2.00) Hypoplastic left heart syndrome↘ (PPR: 0.76, 95% CI: 0.51, 1.13) Coarctation of aorta↔ (PPR:0.99, 95% CI: 0.76, 1.29) Tetralogy of Fallot ↘ (PPR:0.85, 95% CI: 0.64, 1.12) Interrupted aortic arch ↗

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Table 1 (*continued*)

Researchers	Location	Population, outcome and study design	Exposure evaluation approach	Statistical approach and Exposure levels	Confounders	Main findings
						(PPR:1.57, 95% CI: 0.85, 2.92) Total anomalous pulmonary venous connection ↗ (PPR:1.55, 95% CI: 0.98, 2.43) NTD: Spina Bifida↗ (PPR: 1.22, 95% CI: 0.91, 1.65) Anencephaly ↘ (PPR: 0.88, 95% CI: 0.48, 1.61) Cleft lip or palate: Cleft lip only ↘ (PPR: 0.85, 95% CI: 0.64, 1.12) Cleft palate only↗ (PPR: 1.12, 95% CI: 0.92, 1.38) Similar results were reported using the different buffers and further adjustment.
McKenzie et al., 2019(McKenzie et al., 2019a)	Colorado, (USA) Oil and gas	**Population:** All non-chromosomal CHD cases (469) and randomly selected controls, matched by race/ethnicity, sex, maternal smoking status use (2860 controls) from a cohort of 175,533 singleton births born between 2005 and 2011 to mothers living in 34 Colorado counties with 20 or more wells drilled (well starts) per 10,000 births. **Outcomes**: Pulmonary artery and valve defects; aortic artery and valve defects; Conotruncal defects; Tricuspid valve defects. **-A nested case-control study**	-Intensity adjusted inverse distance weighted (IA-IDW) of oil and gas*(O&G) well site activity within 10-mile radius of maternal residence for each month from three months prior to conception through the second month of gestation. Adjustment for phase of well development or intensity of operations that occur at the well site model. -IDW counts of oil and gas facilities other than wells was also calculated.	All IDW were log-transformed and IA-IDW was categorized to three levels: Low = 0 to < 1 intensity wells per square mile; medium = 1 to < 403 intensity wells per square mile, high = ≥ 403 intensity wells per square mile.	Adjusted for IDW count of oil and gas facilities other than wells in 10-mile buffer, IA-IDW count of air pollution sources not associated with oil and gas activities, maternal age, and SES group, as well as infant parity and sex. Effect modification, stratified analysis by rural urban zip codes. Adjusted for IDW count of oil and gas facilities other than wells in 10-mile buffer, IA-IDW count of air pollution sources not associated with oil and gas activities in 10-mile buffer, maternal age, and SES group, as well as infant parity and sex.	Adjusted associations between exposure during **second month of pregnancy** and highest category of **IA-IDW** intensity compared to the lowest reference category: Any CHD ↑ (OR: 1.7, 95% CI: 1.1, 2.6) Aortic artery and valve defects ↗ (OR: 1.5, 95% CI: 0.79, 3.0) Pulmonary artery and valve defects ↗ (OR: 1.7, 95% CI: 0.87, 3.2) Conotruncal defects ↗ (OR: 2.0, 95% CI: 0.97, 4.3) Tricuspid valve defects ↗ (OR: 1.1, 95% CI: 0.25, 4.8) **Rural:** Any CHD ↑ (OR: 2.47, 95% CI: 1.3, 4.4) Aortic artery and valve defects ↗ (OR: 2.67, 95% CI: 1.1, 6.1) Pulmonary artery and valve defects ↗ (OR: 1.57, 95% CI: 0.62, 3.9) Conotruncal defects ↑ (OR: 4.07, 95% CI: 1.4, 12) Tricuspid valve defects-less than 5 cases **Urban:** Any CHD ↘ (OR: 0.947, 95% CI: 0.47, 1.9) Aortic artery and valve defects ↘ (OR: 0.737, 95% CI: 0.23, 2.3) Pulmonary artery and valve defects ↗ (OR: 1.77, 95% CI: 0.59, 4.7) Conotruncal defects ↘ (OR: 0.917, 95% CI: 0.30, 2.8) Tricuspid valve defects - less than 5 cases

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Table 1 (*continued*)

Researchers	Location	Population, outcome and study design	Exposure evaluation approach	Statistical approach and Exposure levels	Confounders	Main findings
						Similar associations were observed for Aortic artery and valve defects and attenuated associations for Conotruncal defects and Tricuspid valve defects with exposure to oil and gas well site activities in each of the three months prior to conception through the first gestational month for Aortic artery and valve defects. For Pulmonary artery and valve defects, the strongest association observed with exposures in the two months prior to conception.
Casey et al., (2019) (Casey et al., 2019)	Pennsylvania, (USA)	**Population:** 8371 singleton births without major CM born at Geisinger between January 2009–January 2013, to mothers without a diagnosis of or medication for anxiety or depression prior to conception. **Outcomes**: PTD, term (≥37 weeks) birth weight. **Mediators**: anxiety or depression first diagnosed during pregnancy or a medication first order for an anxiolytic or antidepressant. - Retrospective cohort with stochastic direct and indirect mediation analysis (also called randomized interventional effects).	- Exposure method as detailed in Casey et al. (2015).	- During the study period, 2980 UOG wells were drilled across 12 of the 31 counties that the majority (99%) of mothers resided in. - The total effect of living in highest quartile (exposed-Q4) of UOG activity compared to the other quartiles (unexposed Q1-Q3): Exposed mothers (Q4) had, on average, 130 wells within 20 km of their home, compared to 10 wells for unexposed mothers (Q1-Q3). Exposed mothers lived a median distance of 11.2 km (IQR: 4.0, 18.0) from the nearest UOG well, compared to 24.0 km (IQR: 17.0, 40.7) among unexposed.	Maternal age, maternal race/ ethnicity, season of conception and delivery, delivery hospital, primary care patient status, smoking status, parity, pre-pregnancy BMI, receipt of Medical Assistance, antibiotic order during pregnancy, change in housing value, mean residential greenness during pregnancy, drinking water source, community socioeconomic deprivation quartile, and distance to nearest major road quartile.	**Risk difference** and 95% confidence intervals of living in the highest quartile of UOG activity compared to the lowers quartiles (Q1-Q3): **Outcomes**: -PTD ↑ [4.3(95% CI: 1.1, 7.5) additional PTD cases per 100 women, (similar for women receiving and not receiving Medical Assistance)]. - Term birth weight ↔ **Mediators**: -Antenatal anxiety or depression ↑ [there were 4.3 additional cases per 100 women (95% CI: 1.5, 7.0) Result of **mediation** analysis: -Antenatal anxiety or depression did not explained the associations between UOG and PTD.

UOG-unconventional oil and gas; T-tertile; IDW-Inverse distance weighted; PTD-preterm birth (< 37 weeks completed gestation); TLBW- term low birth weight (≥37 weeks completed gestation and birth weight < 2500 g); LBW- birthweight smaller than 2500 g; NTD-neural tube defects; CHD-congenital heart defects; Q- Quartile, CI- confidence interval, CM-congenital malformation; Infant health index -a measure that incorporates a number of health outcomes in order to reduce the number of statistical tests, includes birth weight, LBW, PTD, CM; Extremely PTD - births before 28 completed weeks of gestation; Very PTD - births after 27 and before 32 completed weeks of gestation; Moderately PTD-births after 31 and before 37 completed weeks of gestation; SGA -small-for-gestational age - birth weight for gestational age and sex smaller then 10th percentile. *(O&G) Unconventional and conventional oil and gas combined.

↑ = significant increase; ↓ = significant decrease; ↗ = non-significant increase; ↘ = non-significant decrease; ↔ = non-significant direction not reported or zero effect. Significant increase in a measurement may or may not be an improvement.

Table 2
Main characteristics and results of the studies on hospitalizations, asthma exacerbations and indicators of cardiovascular disease.

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
Jemielita et al., (2015) (Jemielita et al., 2015)	Pennsylvania, Bradford, Susquehanna, and Wayne counties (USA)	**Population**: 157,311, and 93,000 inpatient hospital admissions records were identified, from 2007 to 2011. **Outcomes**: 25 medical subcategories were evaluated -**Ecological study**	-Number of operative wells per zip code -Density (wells per km^2) by year for every statistical area.	Conditional fixed effects Poisson regression was used, to control for all possible characteristics of the zip codes, both measured and unmeasured, that did not change during the period of observation. Bonferroni correction was used (*P-value* < 0.00096). The density of the exposure level was categorized and compared to the reference: Reference (66th percentile): 0 wells/km^2. Q1(66–80th percentiles): 0 to 0.168 wells/km^2;Q2 (80–90th percentiles): 0.168 to 0.786 wells/km^2; Q3 (more than 90th percentile): more than 0.786 wells/km^2.	No specific confounders were evaluated. Instead, conditional fixed effects Poisson regression was used, where the fixed effects are the zip codes.	A one-unit increase in the **number of wells** (Relative risk, RR), (*P-value*): Inpatient total ↗ (RR:1.0003), (0.076) Cardiology ↑ (RR:1.0007), (0.0007) Dermatology ↗ (RR:1.0010), (0.039) Endocrine ↗ (RR:1.0008), (0.086) Gastroenterology ↗ (RR:1.0003), (0.338) General medicine ↗ (RR:1.0002), (0.574) Generals surgery ↗ (RR:1.0000), (0.849) Gynecology ↗ (RR:1.0002), (0.708) Hematology ↘ (RR: 0.9997), (0.657) Neonatology ↗ (RR:1.0014), (0.018) Nephrology ↘ (RR: 0.9998), (0.461) Neurology ↗ (RR:1.0006), (0.037) Normal newborns ↔ (1.0000), (0.969) Ob/delivery ↗ (RR:1.0002), (0.411) Oncology ↗ (RR:1.0015), (0.004) Ophthalmology ↗ (RR: 1.0010), (0.593) Orthopedics ↘ (RR: 0.9993), (0.011) Other/ob ↗ (RR:1.0003), (0.727) Otolaryngology ↔ (RR:1.0000), (0.982) Psych/drug abuse ↗ (RR:1.0004), (0.073) Pulmonary ↔ (RR:1.0000) (0.850) Rheumatology ↗ (RR: 1.0014), (0.043) thoracic surgery ↗ (RR:1.0011), (0.100) Trauma ↗ (RR:1.0008), (0.174) Urology ↗ (RR:1.0010), (0.012) Vascular surgery ↗ (RR:0.9997), (0.539) Exposure to the **highest quantile compared to the reference category** of the UOG density, (Relative risk, RR), (*P-value*): Inpatient total ↗ (RR: 1.108), (0.041) Cardiology ↗ (RR:1.27), (0.001) Dermatology ↗ (RR:1.454), (0.013) Endocrine ↗ (RR: 1.391), (0.029) Gastroenterology ↗ (RR: 1.105), (0.364) General medicine ↘

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Table 2 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
						(RR:0.985), (0.872) Generals surgery ↘ (RR: 0.944), (0.424) Gynecology ↘ (RR: 0.967), (0.849) Hematology ↗ (RR: 1.221), (0.429) Neonatology ↗ (RR: 1.527), (0.100) Nephrology ↗ (RR: 1.151), (0.211) Neurology↗ (RR: 1.188), (0.062) Normal newborns ↘ (RR: 0.964), (0.731) Ob/delivery ↗ (RR: 1.029), (0.749) Oncology ↗ (RR: 1.815), (0.002) Ophthalmology ↗ (RR: 1.116), (0.836) Orthopedics ↗ (RR: 0.875), (0.130) Other: ↗ (RR: 1.264) (0.502) Otolaryngology ↗ (RR: 1.004) (0.988) Psych/drug abuse ↗ (RR: 1.13 (0.145) Pulmonary ↗ (RR: 1.067) (0.572) Rheumatology ↗ (RR: 1.866), (0.034) Thoracic surgery 1.13 (0.654) Trauma ↗ (RR: 1.265), (0.222) Urology ↗ (RR: 1.24), (0.215) Vascular surgery ↘ (RR: 0.966), (0.857) Results for analysis of the number of wells are reported only to the cardiology category.
Werner et al., (2016) (Werner et al., 2016)	Queensland, (Australia)	**Population**: 459,549 hospital admissions from 1995 to 2011 across the coal seam gas (CSG) area, coal mining area and rural/ agricultural area. **Outcomes**: 19 ICD-9 categories were evaluated -**Ecological study**	Three areas were compared (CSG area, coal mining area and rural/ agricultural area.)	Negative binomial regression models, offset by the log of the population, were used to evaluate changes in time of rates of hospitalization in statistical local areas that were aggregated to three areas and then compared. Level of exposure was not reported and only a figure showing Queensland's CSG gas production over the study time period was presented.	Adjusted for age, sex, proportion indigenous, proportion Australian-born, proportion employed full-time, proportion white collar, median household income, mean household size. Aggregated on statistical area level.	Hospitalization rate ratio (RR) for all-ages in the CSG area **compared to the rural low-impact area**: All-cause ↗ (RR:1.01, 95% CI: 0.99, 1.04); Neoplasms ↑ (RR:1.09, 95% CI: 1.02,1.16); Blood/immune ↑ (RR:1.14, 95% CI: 1.02, 1.27); Nervous system ↗ (RR:0.99, 95% CI: 0.95, 1.04); Eye ↗ (RR:1.03,95% CI: 0.98, 1.08); Hospitalization rate ratio (RR) for all-ages in the CSG area **compared to the coal high-impact area**: All-cause ↗ (RR: 1.02, 95% CI: 1.00–1.04) Neoplasms ↗ (RR:1.01, 95% CI: 0.96, 1.07) Blood/immune ↗ (RR:1.08, 95% CI: 0.97, 1.20)

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Table 2 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
						Nervous system ↗ (RR:1.03, 95% CI: 0.99, 1.08) Eye ↗ (RR:1.01, 95% CI:0.95, 1.06)
Rasmussen et al., 2016(Rasmussen et al., 2016)	35 counties in Pennsylvania (USA)	**Population**: Asthma patients aged 5–90 years (n = 35,508) nested within a cohort of 400,000 patients in the Geisinger Clinic. Cases were matched by age, sex, and year of event to those without outcome. **Outcomes**: mild, moderate, and severe asthma exacerbations (new oral corticosteroid medication order), emergency department encounter, and hospitalization. -**Nested case-control.**	Estimated activity metrics for four different phases were calculated (pad preparation, drilling, stimulation and production) using IDW squared method, well characteristics, dates/durations of phases and total depth and volume metrics (surrogates for truck traffic and fugitive emissions/compressor engine activity).	Between 2005 and 2012, 6253 UOG wells were spudded on 2710 pads, 4728 were stimulated, and 3706 were in production. The median number of wells per pad was 1 (IQR 1–3) and median total depth was 3,394m (IQR 2934–3839). Most developments occurred after 2007. Each UOG phase was categorized and compared to the reference: Pad activity metric: Reference: less than 10.7; Low: 10.7 to 25.7; Medium:25.8 to 48.7; High: greater than 48.7. Spud activity metric: Reference: less than 5.1; Low:5.1 to 32.3; Medium, 32.4 to 66.8; High: greater than 66.8. Stimulation activity metric: Reference: less than 2.7; Low: 2.7 to 25.5; Medium: 25.6 to 67.4; High: greater than 67.4. Production activity metric: Reference: less than 2.3; Low: 2.3 to 133.2; Medium:133.3 to 759.7; High: greater than 759.7.	Random intercept models for patient and community were used. Models were adjusted for age category, sex, race/ethnicity, family history of asthma, smoking, season, medical assistance, overweight/obesity, for children and adults, type 2 diabetes, community socioeconomic deprivation, distance to nearest major and minor arterial road, squared distance to nearest major and minor arterial road, maximum temperature on the day prior to event (degrees Celsius), and squared maximum temperature on the day prior to event (degrees Celsius)	Exposure to the highest group of the UOG phases compared to the reference group: **Pad activity metric**: Asthma hospitalizations ↑ (OR:1.45, 95% CI: 1.21, 1.73) Asthma emergency department visits ↗ (OR:1.37, 95% CI: 0.94, 1.99)Oral corticosteroid medication orders ↑ (OR:1.59, 95% CI: 1.41, 1.81) **Spud activity metric**: Asthma hospitalizations (OR:1.64, 95% CI: 1.38, 1.97) Asthma emergency department visits ↑ (OR:1.57 (1.08, 2.29) Oral corticosteroid medication orders ↑ (OR:1.99 (1.75, 2.26) **Stimulation activity metric** Asthma hospitalizations ↑ (OR:1.66, 95% CI: 1.38, 1.98) Asthma emergency department visits ↑ (OR:1.71, 95% CI: 1.16, 2.52) Oral corticosteroid medication orders ↑ (OR:3.00, 95% CI: 2.60, 3.45) **Production activity metric**: Asthma hospitalizations ↑ (OR:1.74, 95% CI: 1.45, 2.09) Asthma emergency department visits ↑ (OR:2.19, 95% CI: 1.47, 3.25) Oral corticosteroid medication orders ↑ (OR:4.43, 95% CI: 3.75, 5.22)
Werner et al., 2017 (Werner et al., 2017)	Queensland, Australia	**Population**: 238,457 admissions to hospital for the study area, from 1995 to 2011 **Outcomes**: 19 ICD-9 categories were evaluated -**Ecological and time series study**	CSG well numbers in statistical local areas	Time series regression models were conducted, to investigate the association between quintiles of periods of CSG development activity and monthly hospitalization rates. Level of exposure not reported and only a figure of monthly number of CSG wells and corresponding well categories was presented.	Adjusted for age, sex, proportion of indigenous population, proportion of Australian-born, proportion of employed full-time, proportion of white collar, median household income, mean household size. Aggregated on statistical area level.	Trends in hospitalization rates [hospitalization rates (per 1000 persons) in the very low period, and the intense period], (*P-value* for trend): **Females:** All-cause ↑ [324.0 (295.3–352.8), 390.3 (355.3–425.3)], (0.0003) Blood/immune ↑ [3.4 (0.9–5.9),7.7 (5.1–10.4)], (0.0009) Circulatory ↓ [28.4 (22.7–34.2), 22.3 (16.1–28.5)], (0.0443) Respiratory ↗ [23.7 (17.8–30.0),21.2

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Table 2 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
						(13.8–28.6)], (0.5146) Perinatal ↓ [3.7 (2.3–5.1), 2.5 (1.1–3.8)], (0.0207) Congenital ↗ [0.7 (0.0–1.5), 1.0 (0.3–1.8)], (0.4174) **Male:** All-cause ↑ [294.2 (263.6–324.8), 335.4 (297.7–373.2)], (0.0339) Blood/immune ↗ [3.7 (1.4–5.9), 6.1 (3.8–8.3)], (0.0679) Circulatory ↑ [33.9 (28.7–39.1), 24.3 (18.6–29.9)], (0.0010) Respiratory ↘ [28.4 (21.6–35.2), 26.3 (17.8–34.8)], (0.6931) Perinatal ↓ [3.4 (1.8–5.1), 1.4 (−0.3–3.0)], (0.0089) Congenital ↘ [3.1 (2.2–4.1), 2.4 (1.4–3.4)], (0.0528)
Werner et al., 2018 (Werner et al., 2018)	Queensland, Australia,	**Population**: 80,882 child and adolescent hospital admissions from 1995 to 2011 across the CSG area, coal mining area and rural/agricultural area. **Outcomes**: 19 ICD-9 categories were evaluated. -**Ecological study**	Three areas were compared (CSG area, coal mining area and rural/agricultural area.)	Rates of hospitalization in statistical areas were aggregated to the three categories of exposure Level of exposure was not reported.	Adjusted for age, sex, proportion indigenous, proportion Australian-born, proportion employed full-time, proportion white collar, median household income, mean household size. Aggregated on statistical area level.	Hospitalization rate ratio (RR) for all-ages in the CSG area **compared to the coal high-impact area**: **All-cause** 0–4 years ↔ (RR:1.00, 95% CI:0.98, 1.03) 5–9 years ↑ (RR:1.04, 95% CI:1.00, 1.09) 10–14 years ↘ (RR:0.98, 95% CI:0.94, 1.02) 15–19 years ↗ (RR:1.06, 95% CI:1.00, 1.12) **Infectious disease** 0–4 years ↘ (RR:0.98, 95% CI:0.91, 1.07) 5–9 years ↗ (RR:1.08, 95% CI:0.98, 1.20) 10–14 years ↘ (RR:0.96, 95% CI:0.84, 1.09) 15–19 years ↗ (RR:1.12, 95% CI:0.99, 1.27) **Neoplasms** 0–4 years ↘ (RR:0.87, 95% CI:0.67, 1.13) 5–9 years ↔ (RR:1.00, 95% CI:0.68, 1.49) 10–14 years ↘ (RR:0.89, 95% CI:0.69, 1.15) 15–19 years ↗ (RR:1.05, 95% CI:0.95, 1.17) **Blood/immune** 0–4 years ↘ (RR:0.96, 95% CI:0.67, 1.37) 5–9 years ↘ (RR:0.95, 95% CI:0.33, 2.77) 15–19 years ↓ (RR:0.61, 95% CI:0.38, 0.98) **Endocrine** 0–4 years ↗ (RR:1.07, 95% CI:0.88, 1.30) 5–9 years ↗ (RR:1.03, 95% CI:0.73, 1.44) 10–14 years ↓ (RR:0.75, 95% CI:0.58, 0.95) 15–19 years ↓ (RR:0.66, 95% CI:0.51, 0.86) **Mental disorders**

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Table 2 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
						10–14 years ↘ (RR:0.87, 95% CI:0.70, 1.08) 15–19 years ↘ (RR:0.95, 95% CI:0.84, 1.07) **Nervous system** 0–4 years ↗ (RR:1.08, 95% CI:0.91, 1.27) 5–9 years ↗ (RR:1.02, 95% CI:0.83, 1.25) 10–14 years ↘ (RR:0.86, 95% CI:0.69, 1.07) 15–19 years ↗ (RR:1.05, 95% CI:0.85, 1.29) **Eye** 15–19 years ↗ (RR:1.17, 95% CI:0.82, 1.68) **Ear** 0–4 years ↗ (RR:1.04, 95% CI:0.97, 1.11) 5–9 years ↗ (RR:1.07, 95% CI:0.97, 1.19) 10–14 years ↗ (RR:1.02, 95% CI:0.87, 1.20) **Circulatory** 0–4 years ↓ (RR:0.71, 95% CI:0.51, 0.98) 5–9 years ↗ (RR:1.13, 95% CI:0.84, 1.54) 15–19 years ↗ (RR:1.02, 95% CI:0.81, 1.27) **Respiratory** 0–4 years ↑ (RR:1.07, 95% CI:1.04, 1.11) 10–14 years ↑ (RR:1.09, 95% CI:1.01, 1.18) 15–19 years ↔ (RR:1.00, 95% CI:0.92, 1.08) **Digestive** 0–4 years ↔ (RR:1.00, 95% CI:0.95, 1.06) 5–9 years ↗ (RR:1.04, 95% CI:0.96, 1.12) 10–14 years ↗ (RR:1.07, 95% CI:0.99, 1.17) 15–19 years↑ (RR:1.08, 95% CI:1.02, 1.14) **Skin** 0–4 years ↘ (RR:0.98, 95% CI:0.88, 1.09) 5–9 years ↘ (RR:0.91, 95% CI:0.80, 1.05) 10–14 years ↘ (RR:0.97, 95% CI:0.86, 1.10) 15–19 years ↗ (RR:1.10, 95% CI:0.98, 1.22) **Musculoskeletal** 0–4 years ↘ (RR:0.97, 95% CI:0.74, 1.26) 5–9 years ↗ (RR:1.13, 95% CI:0.87, 1.45) 10–14 years↗ (RR:1.05, 95% CI:0.90, 1.21) **Genitourinary** 0–4 years ↘ (RR:0.99, 95% CI:0.89, 1.09) 5–9 years↗ (RR:1.10, 95% CI:0.93, 1.29) 10–14 years ↗ (RR:1.14, 95% CI:0.97, 1.34) 15–19 years ↘ (RR:0.99, 95% CI:0.91, 1.09) **Pregnancy** 15–19 years ↗ (RR:1.02, 95% CI:0.96, 1.08)

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Table 2 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
						Perinatal 0–4 years ↘ (RR:0.89, 95% CI:0.84, 0.93) **Congenital** 0–4 years ↗ (RR:1.08, 95% CI:0.99, 1.17) 5–9 years ↗ (RR:1.18, 95% CI:0.99, 1.41) 10–14 years ↗ (RR:1.07, 95% CI:0.85, 1.34) 15–19 years ↘ (RR:0.84, 95% CI:0.60, 1.16) **Symptoms necrotizing enterocolitis** 0–4 years ↘ (RR:0.93, 95% CI:0.86, 1.01) 10–14 years ↘ (RR:0.95, 95% CI:0.86, 1.05) 15–19 years↘ (RR:0.94, 95% CI:0.86, 1.04) **Injuries** 0–4 years ↗ (RR:1.03, 95% CI:0.97, 1.10) 5–9 years ↗ (RR:1.01, 95% CI:0.96, 1.07) 10–14 years ↘ (RR:0.98, 95% CI:0.93, 1.04) 15–19 years ↗ (RR:1.06, 95% CI:1.00, 1.11) Hospitalization rate ratio (RR) for all-ages in the CSG area **compared to the rural low-impact area:** **All-cause** 0–4 years ↗ (RR:1.02, 95% CI:0.99, 1.05) 5–9 years ↑ (RR: 1.09, 95% CI:1.04, 1.14) 10–14 years ↗ (RR:1.03, 95% CI:0.98, 1.08) 15–19 years ↗ (RR:1.05, 95% CI:0.99, 1.12) **Infectious disease** 0–4 years ↗ (RR:1.05, 95% CI:0.95, 1.15) 5–9 years ↑ (RR: 1.12, 95% CI:1.00, 1.25) 10–14 years ↗ (RR:1.07, 95% CI:0.93, 1.24) 15–19 years ↗ (RR:1.04, 95% CI:0.91, 1.18) **Neoplasms** 0–4 years ↘ (RR: 0.85, 95% CI:0.60, 1.19) 5–9 years ↑ (RR:1.95, 95% CI:1.27, 3.00) 10–14 years↗ (RR:1.22, 95% CI:0.87, 1.71) 15–19 years ↑ (RR:1.18, 95% CI:1.04, 1.33) **Blood/immune** 0–4 years ↗ (RR:1.23, 95% CI:0.82, 1.83) 5–9 years ↑ (RR:5.67, 95% CI:2.39, 13.44) 15–19 years ↘ (RR:0.86, 95% CI:0.56, 1.31) **Endocrine** 0–4 years↗ (RR:1.25, 95% CI:0.99, 1.57) 5–9 years↗ (RR:1.03, 95% CI:0.71, 1.47) 10–14 years ↓ (RR:0.66,

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Table 2 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
						95% CI:0.51, 0.85) 15–19 years ↓ (RR:0.75, 95% CI:0.60, 0.95) **Mental disorders** 10–14 years ↘ (RR:0.96, 95% CI:0.74, 1.23) 15–19 years ↑ (RR:1.17, 95% CI:1.04, 1.32) **Nervous system** 0–4 years ↘ (RR: 0.91, 95% CI:0.76, 1.09) 5–9 years ↘ (RR:0.99, 95% CI:0.81, 1.21) 10–14 years ↗ (RR:1.12, 95% CI:0.89, 1.40) 15–19 years ↘ (RR:0.90, 95% CI:0.71, 1.13) **Eye** 15–19 years ↗ (RR:1.09, 95% CI:0.73, 1.64) **Ear** 0–4 years ↔ (RR:1.00, 95% CI:0.92, 1.09) 5–9 years ↗ (RR:1.12, 95% CI:0.99, 1.27) 10–14 years ↗ (RR:1.03, 95% CI:0.85, 1.24) **Circulatory** 0–4 years ↘ (RR:0.81, 95% CI:0.55, 1.19) 5–9 years ↘ (RR: 0.91, 95% CI:0.65, 1.26) 15–19 years ↘ (RR:0.96, 95% CI:0.73, 1.27) **Respiratory** 0–4 years ↑ (RR:1.06, 95% CI:1.02, 1.10) 10–14 years ↑ (RR:1.11, 95% CI:1.01, 1.21) 15–19 years ↔ (RR:1.00, 95% CI:0.92, 1.09) **Digestive** 0–4 years↗ (RR:1.03, 95% CI:0.97, 1.11) 5–9 years ↘ (RR:0.99, 95% CI:0.91, 1.08) 10–14 years ↑ (RR:1.19, 95% CI:1.07, 1.31) 15–19 years ↔ (RR:1.00, 95% CI:0.94, 1.07) **Skin** 0–4 years ↗ (RR:1.02, 95% CI:0.89, 1.16) 5–9 years ↗ (RR:1.10, 95% CI:0.93, 1.30) 10–14 years ↘ (RR:0.89, 95% CI:0.76, 1.04) 15–19 years ↔ (RR:1.00, 95% CI:0.88, 1.13) **Musculoskeletal** 0–4 years ↘ (RR:0.78, 95% CI:0.56, 1.08) 5–9 years ↑ (RR:1.36, 95% CI:1.03, 1.81) 10–14 years ↗ (RR:1.06, 95% CI:0.90, 1.25) **Genitourinary** 0–4 years ↘ (RR:0.97, 95% CI:0.85, 1.10) 5–9 years ↗ (RR:1.16, 95% CI:0.95, 1.42) 10–14 years ↗ (RR:1.18, 95% CI:0.99, 1.41) 15–19 years ↔ (RR:1.00,

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Table 2 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
						95% CI:0.90, 1.10) **Pregnancy** 15–19 years ↗ (RR:1.05, 95% CI:0.98, 1.12) Perinatal 0–4 years ↘ (RR:0.94, 95% CI:0.89, 1.00) **Congenital** 0–4 years ↑ (RR:1.12, 95% CI:1.02, 1.23) 5–9 years ↘ (RR:0.95, 95% CI:0.78, 1.16) 10–14 years ↘ (RR:0.93, 95% CI:0.73, 1.17) 15–19 years ↘ (RR:0.87, 95% CI:0.62, 1.22) **Symptoms necrotizing enterocolitis** 0–4 years ↘ (RR:0.99, 95% CI:0.90, 1.08) 10–14 years ↔ (RR:1.00, 95% CI:0.89, 1.13) 15–19 years ↗ (RR:0.91, 95% CI:0.82, 1.02) **Injuries** 0–4 years ↔ (RR:1.00, 95% CI:0.93, 1.07) 5–9 years ↑ (RR:1.08, 95% CI:1.01, 1.15) 10–14 years ↗ (RR:1.02, 95% CI:0.96, 1.09) 15–19 years ↗ (RR:1.03, 95% CI:0.97, 1.10)
Peng et al., 2018(Peng et al., 2018)	Pennsylvania (USA)	**Population**: All inpatient hospital admission records during 2001–2013 **Outcomes**: acute myocardial infarction (AMI), chronic obstructive pulmonary disease (COPD), asthma, pneumonia, and upper respiratory infection (URI) hospitalization. - **Difference-in-differences panel analysis.**	The annual gas production for each active UOG well after its spud date and the number of wells per county and year were calculated.	The county fixed effects and year fixed effects were used. Lag of one was selected. Changes in hospitalization rates over time in counties with UOG wells relative to the change in hospitalization rates over time in counties without UOG wells (with a similar number of counties in each group). Total well number counties (those with at least one UOG well): 7438 UOG wells and 35,122 conventional gas wells. Range: 1–1219 UOG wells/county.	All models include county and year fixed effects, variables at the county level: average age, the share of different types of insurance, the share of female patients, the share of different race and ethnicity groups the share of different types of admission average Charlson index, county-level unemployment rate, poverty rate, annual quartiles of median household income, log of population density, log of annual coal production, log of number of conventional wells, log of conventional output, and the entire county-level age distribution.	The increase of pneumonia admissions per 1000 people in the current year and previous year, by age category, **for UOG well development**: **Current year:** All age (Age 5 and above): ↗ (0.149) Age 5–19: ↗ (0.098) Age 20–44: ↗ (0.026) Age 45–64: ↗ (0.019) Age 65 and above: ↗ (0.506) **Last year:** All age (Age 5 and above): ↗ (0.223) Age 5–19: ↗ (0.061) Age 20–44: ↗ (0.013) Age 45–64: ↗ (0.115) Age 65 and above: ↑ (0.995) Results for AMI, COPD, asthma and URI are not reported in the main text, and the effects were sensitive to the method as well as to the specification of the models.
Willis et al., 2018 (Willis et al., 2018)	Pennsylvania Rural counties fully located on the Marcellus shell (USA)	**Population**: 15,837 patients hospitalization admissions between the ages 2 and 18 years, with acute asthma exacerbations, between 2003 and 2014 **Outcomes**: pediatric asthma	The number of wells drilled in the zip code in a specific quarter of a calendar year	A binary variable for a newly spudded (initially drilled) well, a binary cumulative variable for ever-spudded wells, and tertiles of cumulative count of the wells ever drilled were studied. In total, 5649 UOG wells drilled in the	Age stratification (2–6, 7–12, and 13–18 years) Multilevel mixed effects logistic regression models with a random intercept for zip code and fixed effects for year and quarter were used. Adjusted for sex, race, year, quarter, insurance status, zip	Pediatric asthma-related hospitalization OR: For exposure to **newly** spudded UOG wells within zip code, compared to those who did not live in these communities: All children and adolescents ↑ (OR:1.25, 95% CI: 1.07, 1.47)

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Table 2 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
		hospitalizations **-Difference-in-differences, panel analysis.**		area between 2003 and 2014. The number of UOG sites ever drilled within a zip code were categorized to tertiles and the reference category was zip codes with no UOG activity in study period: Low: 1–2, Medium: 3–10, High: more than 11.	code respiratory hazard index, county median household income quartile, county unemployment, county poverty under 18 years old, and county log population density. With conventional gas wells co-occurring within many zip codes across the study period.	2–6 years ↑ (OR: 1.44, 95% CI: 1.18, 1.75) 7–12 years ↗ (OR: 1.03, 95% CI: 0.83, 1.29) 13–18 years ↑ (OR: 1.34, 95% CI: 1.13, 1.60) For residing in a zip code with **any current or previous drilling activity** exposure compared with those who do not live in these communities: All children and adolescents ↑ (OR:1.19, 95% CI: 1.04, 1.36) 2–6 years ↑ (OR:1.35, 95% CI: 1.14, 1.60) 7–12 years ↗ (OR:1.05, 95% CI: 0.88, 1.25) 13–18 years ↑ (OR:1.29, 95% CI: 1.11, 1.49) For exposure to the **highest category** of the number of UOG sites **ever drilled** within a zip code compared with reference category: All children and adolescents ↑ (OR:1.39, 95% CI: 1.14, 1.71) 2–6 years ↑ (OR:1.73, 95% CI: 1.34, 2.23) 7–12 years ↗ (OR: 1.11, 95% CI: 0.84, 1.47) 13–18 years ↑ (OR:1.35, 95% CI: 1.08, 1.70) -For the years 2011–2014, increasing specific air emissions from UOG sites was associated with increased odds of pediatric asthma hospitalizations (for all-ages models: 2,2,4-trimethylpentane, carbon dioxide, formaldehyde, nitrous oxide, VOCs, and x-hexane; for ages 2–6 also carbon monoxide, methane, nitrogen oxides, PM2.5, PM10, toluene, and xylenes).
Denham et al., 2019 (Denham et al., 2019)	Pennsylvania, (USA)	**Population**: the annual county-level total population. (based on the population estimates from the Surveillance, Epidemiology, and End Results program.) **Outcomes**: 16 major ICD-9 categories from all inpatient discharged data from 2003 to 2014, Pennsylvania. **-Ecological study**	UOG wells drilled into the Marcellus Shale with the start drilling date between 2003 and 2014, aggregated to county-year level and used three annual county-specific exposure measures: Contemporaneous wells (i.e. UOG wells drilled in a year), cumulative well count (i.e. the total number of UOG wells drilled up to the end of that year), and cumulative well density (i.e. cumulative well count divided by the county land area in square kilometers).	A county and year fixed effects multivariate linear regressions was used. First exploratory analysis of 17 × 6 subsets of results (16 major groups and all-cause for 6 subsets (3 exposure categories x all counties and only rural counties)	All models include county and year fixed effects, variables at the county level: distributions by age, sex, race/ethnicity, poverty estimates, median income unemployment rates, county-level hospital counts, uninsured rate (proxy variable, the number of uninsured hospitalizations in a county year divided by the total annual county population).	Associations between increase in a well density and hospitalization rate ratio (RR, 95% CI) per 10,000, for), (*P-value*) (significant associations sign ↑, after correction for multiple testing), **for all counties**: All-cause↗ (RR: 64.3, 95% CI: 178.9307.4), (0.60) Infectious diseases ↘ (RR: 27.7, 95% CI: 52.0,-3.5), (0.03) Neoplasms ↔ (RR: 1.1, 95% CI: 7.9,10.1), (0.81) Endocrine/immune ↗ (RR: 13.3, 95% CI: 10.00,36.6), (0.26) Blood ↘ (RR: 2.75, 95%

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Table 2 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
						CI: 6.4, 0.9), (0.14) Mental disorders ↔ (RR: 7.8, 95% CI: 23.3, 38.8), (0.62) Nervous system ↗ (RR: 10.3, 95% CI: 4.7, 25.4), (0.18) Circulatory ↔ (RR: 26.6, 95% CI: 54.4, 107.7), (0.51) Respiratory ↔ (RR: 8.6, 95% CI: 41.4, 58.6), (0.73) Digestive ↔ (RR: 4.8, 95% CI: 23.3, 32.9), (0.74) Genitourinary ↑ (RR: 20.00, 95% CI: 8.2, 31.8), (0.001) Pregnancy ↔ (RR: 0.4, 95% CI: 10.7, 10.0), (0.94) Skin ↗ (RR: 7.9, 95% CI: 1.4, 17.3), (0.10) Musculoskeletal ↘ (RR: 13.7, 95% CI: 27.1, −0.4), (0.04) CM ↔ (RR: 0.5, 95% CI: 1.2, 2.2), (0.55) Perinatal ↔ (RR: 0.6, 95% CI: 2.7, 3.8), (0.74) Injuries ↔ (RR: 7.4, 95% CI: 22.4, 37.2), (0.62) Associations between increase in a well density and hospitalization rate ratio (RR, 95% CI) per 10,000, for), (*P-value*) (significant associations sign ↑, after correction for multiple testing), **excluding large metropolitan counties**: All-cause ↔ (RR: 125.5, 95% CI: 195.2, 446.3), (0.44) Infectious diseases ↘ (RR: 29.0, 95% CI: 58.4,0.4), (0.05) Neoplasms ↗ (RR: 1.6, 95% CI: 9.4,12.7), (0.05) Endocrine/immune ↔ (RR: 14.9, 95% CI: 15.3, 45.2), (0.33) Blood ↔ (RR: 1.2, 95% CI: 5.0, 2.5), (0.51) Mental disorders ↔ (RR: 15.7, 95% CI: 21.3, 52.8), (0.40) Nervous system ↔ (RR: 10.5, 95% CI: 9.8, 30.7), (0.31) Circulatory ↔ (RR: 41.7, 95% CI: 63.2, 146.6), (0.43) Respiratory ↔ (RR: 20.1, 95% CI: 40.6, 80.9), (0.51) Digestive ↔ (RR: 11.5, 95% CI: 25.2, 48.2), (0.53) Genitourinary ↑ (RR: 23.1, 95% CI: 8.7, 37.5), (0.002)

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exposure levels, confounders and main findings (Tables 1–5).

3. Results and discussion

3.1. Locations, publication dates, and study designs

All studies but three (from Queensland, Australia (Werner et al., 2017, 2018, 2015) were conducted in the United States, in particular Pennsylvania (N = 15), Colorado (N = 5), Texas (N = 2), Oklahoma (N = 1), Ohio (N = 1), and in multiple states (N = 2). All studies were published after 2013 with the majority published between 2017 and 2019 (N = 19).

All epidemiological studies were observational and retrospective (i.e., no prospective studies were identified) or cross-sectional. Of the

Table 2 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
						Pregnancy ↔ (RR: 1.3, 95% CI: 11.1, 13.6), (0.84) Skin ↑ (RR: 12.2, 95% CI: 4.5, 20.0), (0.002) Musculoskeletal ↔ (RR: 6.9, 95% CI: 23.3, 9.6), (0.41) CM ↔ (RR: 0.29, 95% CI: 1.8, 2.4), (0.78) Perinatal ↔ (RR: 0.07, 95% CI: 4.1, 4.3), (0.97) Injuries ↔ (RR: 9.6, 95% CI: 30.6, 49.8), (0.63) Similar associations with well counts.
McKenzie et al. 2019 (McKenzie et al., 2019b)	Northeastern Colorado, (USA)	**Population**: Between October 2015 and May, 2016, 97 participants(28 men and 69 non-pregnant women, ≥18 years who did not smoke tobacco or marijuana, not taking statins or other anti-inflammatory medication; not occupationally exposed to dust, fumes, solvents, or oil and gas development activities; not frequently exposed to environmental tobacco or marijuana smoke; and without a history of diabetes, chronic obstructive pulmonary disease, or chronic inflammatory diseases (such as asthma, arthritis, or severe allergies), and resided full-time in the city of Fort Collins, (n = 46), or in the cities of Windsor or Greeley, (n = 51) **Outcomes**: augmentation index, blood pressure, systemic inflammation (Interleukin (IL)-1β, IL-6, IL-8 and tumor necrosis factor alpha (TNF-α)) -**a cross-sectional study**	-Intensity adjusted inverse distance weighted (IA-IDW) of oil and gas*(O&G) as described in (McKenzie et al., 2019a) within 16 km (10 miles) of a participant's home	IA-IDW distribution was divided into tertiles, lowest tertile as the referent group: T1, low: (0–14.5 well intensity/kilometer^2) T2, Medium: (14.6–1242 well intensity/kilometer^2): T3: High: more than 1242 well intensity/kilometer^2)	Adjusted for age, sex, race/ethnicity, BMI, education, income, and employment. Stratification by prescription medication use.	Differences in means in the highest tertile compared to the lowest tertile of IA-IDW: Augmentation index ↑ (6.0, 95% CI: 0.6, 11.4) Systolic blood pressure ↗ (3, 95% CI: −3, 8) Diastolic blood pressure ↗ (2, 95% CI: −1, 6) IL-1β (0.064, 95% CI: −0.022, 0.149) IL-6 ↔ (−0.062, 95% CI: −0.256, 0.125) IL-8 ↔ (−0.079, 95% CI: −1.25, 1.05) TNF-α ↗ (0.329, 95% CI: −0.632, 1.27) **No prescription medications**: Systolic blood pressure ↑ (6, 95% CI: 0.1, 13) Diastolic blood pressure ↗ (4, 95% CI: −1, 8) **One or more prescription medications**: Systolic blood pressure ↔ (−0.6, 95% CI: 7, 5) Diastolic blood pressure ↗ (1, 95% CI: −3, 6)

AMI -acute myocardial infarction, CSG-coal seam gas; COPD-chronic obstructive pulmonary disease; CI- confidence interval; IDW- inverse distance weighted or inverse-distance squared weighted methods; IA-IDW - intensity adjusted inverse distance weighted; ICD-9- International Classification of Diseases, Ninth Revision; IL-Interleukin; Q- Quartile; UOG-unconventional oil and gas; T-tertile; URI -upper respiratory infections; RR-Rate ratio; OR – odds ratio.
↑ = significant increase; ↓ = significant decrease; ↗ = non-significant increase; ↘ = non-significant decrease; ↔ = non-significant direction not reported or zero effect. Significant increase in a measurement may or may not be an improvement.

Table 3
Main characteristics and results of the studies on cancer incidence.

Researchers	Location	Population and study design	Outcomes measured	Approach to evaluate the exposure	Statistical approach and exposure levels	Confounders	Main findings
Fryzek et al., 2013*(O&G) (Fryzek et al., 2013)	Pennsylvania (USA)	Childhood (under the age of 20) all cancers (10,708), childhood leukemia (2,568) and childhood central nervous system cases (1,944) diagnosed during 1990–2009. -**Ecological study**	Childhood cancer, leukemia and central nervous system tumors	County counts of wells, before and after establishment of oil and gas (vertical and horizontal) wells.	Standardized incidence ratios (SIRs) for pre- oil or gas well development (1990 to year prior to drilling) and post-development (from year of first UOG to 2009) Level of exposure not reported. Counties with oil and gas wells ranged from 0 to more than 2000 wells.	SIRs calculated (indirectly standardized for age and sex)	Childhood cancer SIRs by counties after compared with pre-horizontally drilled gas wells (those most likely to involve UOG): Childhood all cancers ↘ (SIR before: 0.99, 95% CI: 0.93, 1.09; SIR after: 0.94, 95% CI: 0.84, 1.05). Childhood leukemia ↘ (SIR before: 1.01, 95% CI: 0.93, 1.09; SIR after: 0.93, 95% CI: 0.73, 1.18). Childhood central nervous system ↗ (SIR before: 1.01, 95% CI: 0.92, 1.11; SIR after: 1.06, 95% CI: 0.82, 1.36).
Finkel (2016) (Finkel, 2016)	Southwest Pennsylvania (USA)	Incidence of urinary bladder (57,177), thyroid (31,599), and leukemia (27,670) cases diagnosed during 2000–2012 -**Ecological study**	Urinary bladder, thyroid, and leukemia cancer incidence rates	County counts of wells categorized to high, moderate, and minimal producing wells.	SIRs for 2000–2004, 2004–2008 and 2008–2012. Number of UOG active wells during 2015 Allegheny (63), Beaver (30), Fayette (257), Greene (870), Washington(1146), Westmoreland (251)	SIRs calculated (indirectly standardized for age, sex and race) before drilling activity and after.	SIRs during 2008–2012 compared with SIRs during 2000–2004: Urinary bladder ↑ (SIRs increased in both sexes in counties with shale gas activity) Thyroid cancer ↔ (SIRs increased in both sexes in all counties) Leukemia ↔ (mixed results for males and females and among the counties regardless of the extent of UOG development activities).
McKenzie et al., (2017) (McKenzie et al., 2017)	Rural Colorado (USA)	Childhood (0–24) hematological cancers. 87 acute lymphocytic leukemia (ALL) cases and 50 non-Hodgkin lymphoma cases (NHL), compared to 528 controls with non-hematologic cancers -**A case-control study**	Childhood (0–4 and 5–24) ALL cases and NHL cases	For each child, IDW UOG well counts within 10 miles radius of residence at cancer diagnosis for each year in a 10 year latency period was calculated.	IDW well count tertiles were calculated and zero wells was the reference category. Refernce:0 wells/mile T1:1–4.9 wells/mile T2, 4.9 to 33.6 wells/mile, T3: > 33.6 wells/mile	Age, race, gender, income, elevation and year of diagnosis	Exposure to highest tertiles of UOG compared to zero wells (10 mile): **All ages:** Childhood ALL ↗ (OR: 2.0,95% CI: 0.80, 5.0). Childhood NHL ↘ (OR: 0.99,95% CI: 0.39, 2.5). **0 to 4 Years:** Childhood ALL ↘ (OR: 0.51,95% CI: 0.12, 2.2). Childhood NHL ↔ **5 to 24 Years** Childhood ALL ↑ (OR: 4.6,95% CI: 1.2, 18.0). Childhood NHL ↔

UOG-unconventional oil and gas; T-tertile; IDW-Inverse distance weighted; , CI- confidence interval; ALL-acute lymphocytic leukemia; NHL -non-Hodgkin lymphoma; SIRs Standardized Incidence Ratios; OR – odds ratio
*(O&G)At Fryzek et al., 2013 (Fryzek et al., 2013) 97.5% of wells were non-horizontal wells. ↑ = significant increase; ↓ = significant decrease; ↗ = non-significant increase; ↘ = non-significant decrease; ↔ = non-significant direction not reported or zero effect. Significant increase in a measurement may or may not be an improvement.

Table 4
Main characteristics and results of the studies on sexually transmitted diseases (STD).

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
Komarek and Cseh (2017) (Komarek and Cseh, 2017)	New York, Pennsylvania, Ohio, and West Virginia (USA)	**Population** and **Outcomes**: the annual county-level gonorrhea incidence rates (per 100,000 population) for the years 2003–2013 for four US states. -**Differences-in difference**	Treated counties (those experiencing a fracking boom- 50 or more (or in an alternative specification 33 or more) UOG wells drilled in a year) versus control counties (counties without such boom). The cutoff point for high fracking dummy variable was 50 and 33 UOG wells drilled per year, while the low fracking indicator variable is used for counties with some wells spudded, but fewer than 50 or 33.	Differences in differences approach to compare the change in STD in treated counties (those experiencing a fracking boom) versus control counties (counties without such boom). County and year as fixed effects. Correct the standard errors by clustering at the county level.	For each county unemployment rate, poverty rate, per capita income, population density, percentage of male, percentage of black.	The adjusted impact of UOG activity on gonorrhea (log of gonorrhea incidence per 100,000) in counties with fracking relative to the control counties without. **All counties** Cut off 33 UOG wells(N = 2992): "High fracking": ↑ 0.231; "Low fracking" ↑ 0.188 cut off 50 UOG wells(N = 2992): "High fracking": ↑ 0.248; "Low fracking" ↑ 0.188 **Counties with populations below 250,000** Cut off 33 UOG wells (N = 2562): "High fracking": ↑ 0.234; "Low fracking" ↑ 0.203 Cut off 50 UOG wells(N = 2562): "High fracking": ↑ 0.243; "Low fracking" ↑ 0.203 **Counties above the Marcellus shale** Cut off 33 UOG wells(N = 2178): "High fracking": ↗ 0.2; "Low fracking" ↑ 0.18 Cut off 50 UOG wells(N = 2178): "High fracking": ↗ 0.211; "Low fracking" ↑ 0.18 **Counties above the Marcellus shale with populations below 250,000** Cut off 33 UOG wells(N = 2001): "High fracking": ↑ 0.203; "Low fracking" ↑ 0.19 Cut off 50 UOG wells(N = 2001): "High fracking": ↗ 0.208; "Low fracking" ↑ 0.19 Spudding an additional horizontal well on gonorrhea IR for all above mentioned analysis: ↔
Deziel et al., (2018) (Deziel et al., 2018)	Ohio, (USA)	**Population** and **Outcomes**: cases of chlamydia, gonorrhea, and syphilis by county and year for the years 2000–2016 for 88 counties. The annual cumulative incidence of reported cases in each year and county was estimated per 10,000 population (overall, male, female) -**Ecological study**	All 88 counties were classified as none, low, and high UOG activity in each year. Locations and permit dates of UOG wells were used. Approximately 83% of the permitted wells included in the analysis advanced to drilling and production stages. UOG activity was quantified using a categorical variable for the number of shale gas wells with permits issued per county and year: none (reference-0 wells), low (1–10 wells), and high (> 10 wells). Cut-points indicate the number of new well permits below	Mixed-effects Poisson regression models was used to evaluate the relationship between UOG activity and reported annual STD rates while adjusting for secular trends and potential confounders.	Population density, income, race, ethnicity, access to health care, educational attainment, age, and sex.	Rate ratios (RR) and 95% confidence intervals (95% CI) for the adjusted associations between UOG activity and reported rates of STD high category compared to the none category (N = 1496 county-years): -Chlamydia ↑ (RR:1.21, 95% CI: 1.08, 1.36) -Gonorrhea ↗ (RR:1.19, 95% CI: 0.98, 1.44) -Syphilis ↘ (RR:0.71, 95% CI: 0.44, 1.16)

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Table 4 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
			or above the median among the non-zero values.			
Beleche and Cintina (Beleche and Cintina, 2018)	Pennsylvania, (USA)	**Population** and **Outcomes**: county-year level data from 2003 to 2012(N = 670) on gonorrhea and chlamydia rates, also available by ethnic, gender, and age groups (15–24 and 25–34). Limited to Whites -**Differences-in difference**	In the manuscript Fig. 2 shows the number of conventional and UOG wells in Pennsylvania from 1994 to 2012. The number of conventional wells increased significantly in the late 1990s while the number of UOG wells started to grow at the mid-2000s. At 2009 the number of conventional wells decreased, but the number of UOG wells began to increase at a faster pace than in the preceding years. Measuring UOG development activities or shale booms with a variable that:1) captures any type of conventional and UOG wells, 2) the total number of UOG wells, 3)the presence of any conventional wells, 4) the presence of UOG wells only, 5) the presence of UOG wells and 6) the total number of conventional wells.	Difference-in-differences methodology was used.	Adjustment for unemployment rate, number of hospitals, and number of mental and substance abuse facilities in a county-year, oil and gas production (conventional and UOG), coal production, officers per 1000 population, county fixed effects, year fixed effects, and county-specific linear trends. Standard errors clustered at the county level. Regressions were weighted by county-level population.	The estimated associations between the STD rates in counties compared to counties without conventional and unconventional oil and gas wells: -Gonorrhea rate ↑ (7.8% increase) -Chlamydia rate ↑ (2.6% increase)

UOG-unconventional oil and gas; STD – sexually transmitted disease; CI – confidence interval.
↑ = significant increase; ↓ = significant decrease; ↗ = non-significant increase; ↘ = non-significant decrease; ↔ = non-significant direction not reported or zero effect. Significant increase in a measurement may or may not be an improvement.

Table 5
Main characteristics and results of the studies on fatal and major injury truck and traffic accidents.

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
Graham et al., (2015) (Graham et al., 2015)	Pennsylvania, (USA)	**Population**: the denominator was the million vehicle-miles traveled in the county per month per year, from 2005 to 2012). **Outcomes**: the number of traffic accidents (total vehicle accidents, heavy truck, fatal, and major injury accidents) per months per county. Major-injury defined as incapacitating injury, including bleeding wounds and amputations or broken bones that requires transport of the patient from the scene of the accident. **-Ecological study**	The 18 counties with the most drilling were grouped into northern counties (n = 12) and southwestern counties (n = 6), with the southwestern counties having generally higher population and traffic density due to their proximity to the city of Pittsburgh. As of December 2012, 18 of 67 counties in Pennsylvania had more than 50 natural gas wells drilled, 21 counties had fewer than 50 wells, and 28 counties had none. There were fewer than 5 UOG (northern region) and 6 UOG (southwestern region) wells drilled in 2005, peaking at 1421 wells in 2011 and dropping back to 760 in 2012(northern region) and in the southwestern group, the number of new UOG wells drilled per year has risen more steadily to 588 wells in 2012. For each county and month, drilling activity was quantified: (1) as a binary variable (yes or no) indicating whether there were any new wells spudded during the prior, current, or upcoming month; and (2) as a continuous variables counting the number of wells spudded during that 3-month time-frame	1) Generalized estimating equation (GEE) models were used to estimate the marginal (overall mean) differences between county groups within each year. 2) Both a GEE model with exchangeable covariance structure and a fixed-effects model with county-level intercepts were used to estimate the marginal (overall mean) and conditional (within-county) effects of drilling, respectively were used to compare the crash rates during months with vs. without drilling activity (a time-varying property of each county). Monthly observations based on whether there had been drilling activity or not in that particular county during 3 months before the crash. 1) Compared rates of crash events in drilling and non-drilling regions over time, in each calendar year. 2) Compared the crash event rates between months with and without drilling activity.	1) Matching counties with drilling to non-drilling counties with similar population size and traffic in the pre-drilling period (average vehicle traffic volume, heavy-truck traffic volume, vehicle accidents per million miles traveled, heavy-truck accidents per million miles traveled, and population size). Adjustment for month.	Comparison of crash Rate Ratio (RR) between **counties with and without drilling** (in 3-month period): **Northern counties:** **Fatal crashes per million vehicle-miles per month** Conditional (within-county) effect ↔ (RR: 1.04, 95% CI: 0.89, 1.23) Marginal (overall mean) effect ↔ (RR:1.03, 95% CI: 0.94, 1.13) **Major injury crashes per million vehicle-miles per month** Conditional (within-county) effect ↔ (RR:1.04, 95% CI: 0.92,1.17) Marginal (overall mean) effect ↔ (RR: 1.01, 95% CI: 0.88,1.15) **Southwestern counties:** **Fatal crashes per million vehicle-miles per month** Conditional (within-county) effect ↔ (RR: 1.08, 95% CI: 0.90, 1.30) Marginal (overall mean) effect ↗ (RR: 1.12, 95% CI: 0.99–1.27) **Major injury crashes per million vehicle-miles per month** Conditional (within-county) effect ↔ (RR: 0.94, 95% CI: 0.83–1.05) Marginal (overall mean) effect ↔ (RR: 1.01, 95% CI: 0.90–1.13) Comparison of RR between drilling and non-drilling counties, by year and by Northern or Southwest region, from 2005 to 2012: No statistically significant increases in fatal or major injury crashes were seen in the northern drilling counties relative to controls in 2009–2012. For the southwest drilling group, significant differences relative to controls observed for fatal and major injury crashes in 2012 (RR = 1.47, 1.45, respectively, $p < 0.01$) and a higher major injury crash rate in 2009 (RR = 1.28, $p = 0.04$).
Blair et al. 2019 (Blair et al., 2018)	Colorado, (USA)	**Population**: County populations **Outcomes**: number of multivehicle truck accidents with an injury from 2005 to 2013. The incidence of truck accidents per capita was calculated by dividing the annual number of accidents by the annual estimated county population. **-Ecological study**	Unconventional and conventional oil and gas combined *(O&G) Grids of various sizes were overlaid on Colorado in 11 counties: 0.1° by 0.1°, 0.05° by 0.05°, 0.025° by 0.025°, and 0.01° by 0.01°. The number of multivehicle accidents including a truck and injury, homes,	The hurdle model employed a logistic regression model for the incidence process, and a zero-truncated negative binomial regression model (with log link) for the prevalence process. The incidence model is used to show whether more homes and/or wells are associated with a higher	Adjusted to home count (proxy to population density and car density)	The prevalence model shows if more wells are associated with a change in number of accidents with multiple vehicles with an injury. (Estimate, SE) **0.05 by 0.05 degree grid:** Wells ↑ (9.76, 3.28) **0.1 by 0.1 degree grid:** Wells ↑ (8.18, 1.86) The incidence model (used to show

(*continued on next page*)

Table 5 (*continued*)

Researchers	Location	Population, outcomes and study design	Exposure evaluation approach	Statistical approach and exposure levels	Confounders	Main findings
			and O&G wells were counted for each grid cell.	probability of accidents with multiple vehicles with an injury. The prevalence model shows if more homes and/or wells are associated with a change in number of accidents with multiple vehicles with an injury.		whether more wells are associated with a higher probability of accidents with multiple vehicles with an injury. (Estimate, SE) **0.05 by 0.05 degree grid:** Wells ↑ (18.54, 2.29) **0.1 by 0.1 degree grid:** Wells ↑ (8.85, 2.52)

UOG-unconventional oil and gas; GEE – generalized estimating equation; CI- confidence interval; RR-Rate ratio; *(O&G) Unconventional and conventional oil and gas combined; SE- Std. Error.
↑ = significant increase; ↓ = significant decrease; ↗ = non-significant increase; ↘ = non-significant decrease; ↔ = non-significant direction not reported or zero effect. Significant increase in a measurement may or may not be an improvement.

twelve studies on pregnancy outcomes, most were registry-based cohorts (N = 8), of which two used the differences-in-differences design, two were ecological and time series studies, and two used a nested-case control design (Table 1). Out of the nine studies of hospitalization, asthma exacerbations and indicator of cardiovascular disease, most used an ecological design (N = 5), of which one additionally used a time series design, two used the difference-in-differences design, one used a nested case-control design, and one used a cross-sectional design (Table 2). Of the three cancer studies, two used an ecological design and a single study used a case-control design (Table 3). For sexually transmitted diseases, out of the three studies, two studies used the difference-in-differences design and a single study used ecological design (Table 4). The two fatal and major injury car and truck accident studies used an ecological design (Table 5). While all of the above mentioned study designs are well characterized and commonly used in the environmental epidemiology field, the difference-in-differences study design is more commonly used in economic studies (Meyer, 1995). The difference-in-differences research design is a quasi-experimental design that researchers often use to explore causal relationships where randomized controlled trials are infeasible or unethical. It accounts for pre-existing time trends in health outcomes that may have been present prior to the introduction of UOG, allowing for comparison of changes in the outcome over the entire study period, before and after the introduction of UOG ("intervention") in the "treated areas" (those experiencing a UOG development), versus the trends in the "control areas" (those unexposed to UOG). The difference-in-difference methodology assumes that the same trends in the absence of an "intervention" for all areas and that all determinants of the outcomes except the "intervention" evolve identically in the control and treated areas (Wing et al., 2018).

3.2. Exposure assessment approaches

The population exposure to UOG drilling and production activities was evaluated in the different studies using a variety of methods. The methods used to evaluate the level of the exposures of the population in the ecological and time series studies were: categorization of areas with and without wells (Busby and Mangano, 2017; Finkel, 2016; Fryzek et al., 2013; Graham et al., 2015; McKenzie et al., 2019b; Werner et al., 2018, 2015), referring to the number of wells (Denham et al., 2019; Deziel et al., 2018; Jemielita et al., 2015; Ma, 2016; Werner et al., 2017), the spatial density of the wells or of the operative wells (Denham et al., 2019; Jemielita et al., 2015; Ma, 2016) within a specific geographic unit and a specific time period (such as month, year or a few years). Similarly, in the difference-in-differences studies the number of wells or the cumulative gas production within a specific geographic unit and a specific time period was used as the exposure metric (Beleche and Cintina, 2018; Komarek and Cseh, 2017; Peng et al., 2018; Willis et al., 2018).

In the other studies, the distance to the nearest UOG well (nearest neighbor method combined with the spud date) was used (Currie et al., 2017; Hill, 2018) and the inverse distance weighting (a single 10 mile radius (McKenzie et al., 2014; Stacy et al., 2015)) or the inverse-distance squared weighting (IDW) methods (a single 10 miles radius (McKenzie et al., 2017), 0.5 mile, 2 miles and 10 miles radii (Whitworth et al., 2017); 2 miles, 5 miles and 10 miles radii (Janitz et al., 2019)) were used. IDW methods are based on the density of wells in an aerial radius around residence addresses, and account for both the number of UOG wells within this radius and for the distance of each well from the residence address (inverse linear distance: $1/d$ or inverse squared distance: $1/d^2$). IDW provides greater weight to wells closer to the residential addresses. Recent studies also accounted for the specific phase of UOG process (i.e. pad preparation, drilling, stimulation and production) using IDW models that incorporated distance to residence, dates and durations of the phases and well characteristics (without specification of radius (Casey et al., 2019, 2015; Rasmussen et al., 2016), within 0.5 mile radius (Walker Whitworth et al., 2018) or 10 mile radius (McKenzie et al., 2019a, 2019b)). All the studies reported exposure levels based on the address at birth (i.e. not during pregnancy), at the hospitalization or at the time of diagnosis (not accounting for possible changes in address). All the studies, except five studies that could not distinguish between UOG and conventional oil and gas wells (Blair et al., 2018; Fryzek et al., 2013; Janitz et al., 2019; McKenzie et al., 2019a, 2019b), explicitly analyzed the associations with UOG wells. The heterogeneity in exposure assessment methodologies limited the comparability between the studies.

3.3. Summary of the associations between UOG exposure and health outcomes

3.3.1. UOG exposure and adverse pregnancy outcomes

A growing body of literature has attempted to address the potential effects of UOG development on pregnancy outcomes. Focused research on pregnancy outcomes to evaluate the health effects of exposure to UOG have some advantages: first, there is increasing evidence that fetuses are vulnerable to a range of pollutants (Nieuwenhuijsen et al., 2013). Secondly, since the fetus is in utero for about 9 months at most, it is possible to pinpoint the timing of potential exposure, which is not the case for other health outcomes, such as cancer, that have a much longer latency period. In addition, birth data are available, reliable and outcomes such as birth weight and gestational age measured accurately; furthermore, precise information on maternal address enables researchers to examine the effects of proximity to UOG sites on the health of newborns. Pregnancy outcomes were evaluated in twelve of the studies evaluated for this review and focused on fetal growth, gestational length and congenital malformations (Table 1, Fig. 2). All the studies were retrospective analyses of birth certificate records, with birth address data used as a proxy of the address during pregnancy. There was heterogeneity in the outcomes tested, and most studies evaluated more than one outcome.

The seven studies on fetal growth focused on three main outcomes: mean birth weight, low birth weight (LBW, birthweight smaller than 2500 g), and small for gestational age (SGA, birth weight for gestational age and sex smaller then 10th percentile) (Casey et al., 2019, 2015; Currie et al., 2017; Hill, 2018; McKenzie et al., 2014; Stacy et al., 2015; Whitworth et al., 2017). All these studies evaluated the effects on mean birth weight and LBW in all births or in term births (births after 37 completed weeks of gestation) and four of them also evaluated SGA (Casey et al., 2015; Hill, 2018; Stacy et al., 2015; Whitworth et al., 2017). Stacy et al. (2015) reported that living in the highest quartile compared to the lowest of UOG well density was associated with decreased mean birth weight (adjusted change in mean birth weight was −21.8 g (95% CI: (−40.2) - (−3.4)). Sensitivity analysis of births delivered only during 2010, the year in which intensive UOG drilling started in the region, demonstrated similar results. In another study with similar population, when the highest quartile of UOG well activity was compared to the lower three quartiles, no significant associations were reported (Casey et al., 2019). Stacy et al. (2015) also reported an increase in SGA odds across quartiles, which is suggestive of a dose-response relationship (4th quartile vs. 1st quartile OR: 1.34; 95% CI:1.10, 1.63).

Currie et al. (2017) used difference-in-differences design. The researchers developed a metric to evaluate the effect of living near UOG wells prior to and after the start of the drillings. A possible reason why birth outcomes might differ in an area before and after UOG development is that the maternal population may change. To address this problem, the researchers compared each mother to herself (sibling comparison). The results demonstrated that the largest effects were observed for mothers living within 0.6 mile of a UOG well. They reported a 25% increase in the probability of LBW and significant decline

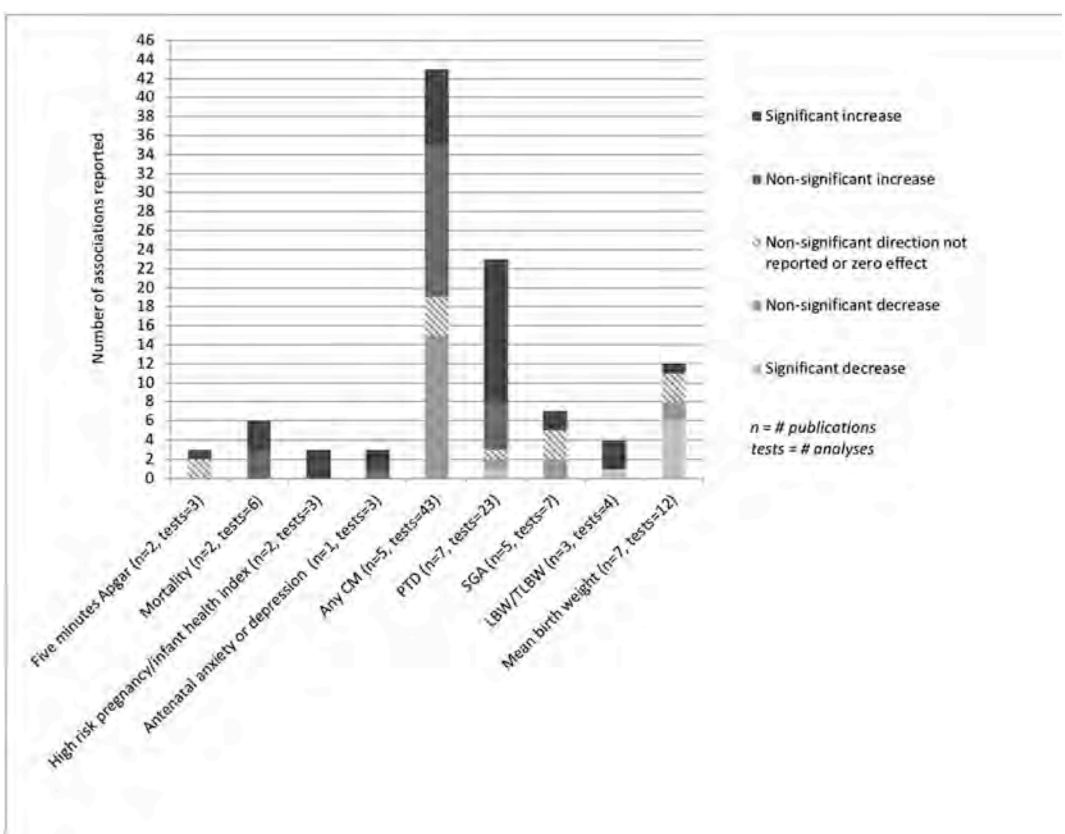

Fig. 2. Summary of the results (number of publications and number of tests of associations) for adverse pregnancy outcomes, the most frequently studied outcome in the published literature.

in the mean birth weight (39 g). The effect estimates reported for mothers living within 0.6–1.8 miles of a UOG well were smaller than those for mothers living within 0.6 mile of a UOG well. There is little evidence to support health effects at farther distances, suggesting that health impacts are local. The effect estimates for models of siblings were very similar but non-significant, due to the smaller sample size. Hill (2018) used a similar approach to Currie et al. (2017) and reported effects at larger distances, with robust results up to 3.1 miles. The author (Hill, 2018) reported that living near shale gas wells (1.5 miles) increased the incidence of LBW by 24%, and term birth weight and birth weight were decreased by 49.6 g and 46.6 g, on average, respectively. They reported that an additional well within 1.5 miles from maternal residence was associated with a 7% increase in LBW and 5 g reduction in term birth weight. Hill (2018) also reported that living near shale gas well development (1.5 miles) increased the incidence of SGA by 18%. However, other studies did not report such robust associations. The results of Casey et al. (2015) (a decrease in term birth weight by 31 g, 95% CI: 57, −5) were not robust when adjusted for year and were non-significant for SGA. Whitworth et al. (2017) also reported non-significant associations for birth weight and SGA. McKenzie et al. (2014) reported inverse associations between living near UOG and term birth weight and LBW, hypothesizing that the inverse results are a type 1 error. A sensitivity analysis conducted using smaller radii, as well as inclusion of births after the year of 2000 (to exclude births before UOG expansion) attenuated the inverse associations. According to the researchers, the inverse associations were possibly causal since stronger associations were found when more stringent exposure estimates were used.

Seven studies evaluated the associations between UOG development and preterm deliveries (PTD) (Casey et al., 2019, 2015; Hill, 2018; McKenzie et al., 2014; Stacy et al., 2015; Walker Whitworth et al., 2018; Whitworth et al., 2017) with most of the studies reporting increased odds of PTD. Casey et al. (2015) considered all active UOG wells during pregnancy and reported increased odds for PTD among women in all UOG activity quartiles, compared to the lowest quartile (2nd/1st (OR 1.3, 95% CI:1.0, 1.8), 3rd/1st (OR 1.6, 95% CI:1.1, 2.4), 4th/1st (OR 1.9, 95% CI:1.2, 2.9)). Additionally, in a restricted analysis carried only for moderate and late PTD cases, increased odds were reported (4th/1st (OR 1.5, 95% CI: 1.0, 2.4)). In addition, risk differences were reported by Casey et al. (2019) for women living in the 4th quartile compared to the 1st -3rd quartiles (4.3 additional PTD cases per 100 women (95% CI: 1.1, 7.5)), Whitworth et al. (2017) reported increased odds of PTD in the highest tertile of UOG wells density compared to zero wells density for the half- (OR: 1.14; 95% CI: 1.03, 1.25), two- (OR 1.14; 95% CI:1.07, 1.22), and 10- (OR 1.15; 95% CI:1.08, 1.22) miles radii. In the same population, Whitworth et al. (Walker Whitworth et al., 2018) reported increased odds of PTD in the 3rd tertile of the UOG drilling (OR 1.20,95% CI:1.06, 1.37) and UOG-production (OR 1.15,95% CI:1.05–1.26) metrics within a radius of half a mile compared to the zero wells category. They found that the strongest associations among women in the 3rd tertile of exposure to UOG drilling metrics and production activity were during the first trimester (OR 1.24; 95% CI:1.03, 1.49; OR 1.18; 95% CI:1.02,1.37; respectively). Analysis by PTD severity (extremely, very, and moderately preterm) (Walker Whitworth et al., 2018) revealed the strongest associations of exposure to UOG drilling metrics and production activity for extreme PTD. Hill (2018) reported for PTD, significant associations (3% increase) for each additional UOG well drilled prior to birth within 2.5 km, but the results were mixed and sensitive to model specifications. However, McKenzie et al. (2014) found a statistically significant inverse association between UOG activity and PTD and Stacy et al. (2015) reported no associations for women in the highest exposure quartiles.

In addition to these pregnancy outcomes, five studies evaluated associations with congenital malformation. These studies evaluated the associations with structural birth defects, functional and developmental malformations, congenital heart defects, neural tube defects, facial malformations, and specific sub-categories of these outcomes. The categorizations used in these studies were different and thus the studies could not be directly compared. McKenzie et al. (2014) reported that exposure to the highest tertile increased the odds of congenital heart defects (OR: 1.3, 95% CI: 1.2, 1.5) and neural tube defects (OR: 2.0; 95% CI: 1.0, 3.9, based on 59 cases) compared with the lowest tertile. Similar associations were reported for congenital heart defects by McKenzie et al. (2019a) for combined exposure to conventional and unconventional oil and gas highest category compared to lowest (OR:1.7, 95% CI:1.1,2.6) and specifically in the rural areas (OR: 2.47, 95% CI:1.3, 4.4). Ma (2016) reported 21% higher structural birth defects (95% CI: 11%–32%) and 23% higher functional or developmental birth defects prevalence rates (95% CI: 6%–43%) in zip codes with UOG compared to zip codes without UOG wells (results were significant also after adjustment to UOG wells density). However, although the results from the spatial models demonstrated significant associations, yearly birth defects prevalence rates in both areas with and without UOG had decreasing trends and were parallel to each other. Therefore, the authors concluded that UOG was not associated with birth defects. Hill (2018) did not find any associations between UOG and any congenital malformations and Janitz et al. (2019) did not find any significant associations between combined exposure to conventional and unconventional oil and gas and congenital heart defects, neural tube defects and facial malformations.

The reviewed studies also evaluated the associations for each of the following outcomes: Apgar score and high risk pregnancy (Casey et al., 2015; Hill, 2018), fetal deaths (Hill, 2018; Whitworth et al., 2017), early infant mortality (0–28 days) (Busby and Mangano, 2017), antenatal anxiety or depression (Casey et al., 2019) and health index (an index that combines the birth weight and indicators for high risk pregnancies, LBW, PTD, the presence of any congenital malformation, and the presence of any other abnormal condition of the newborn) (Currie et al., 2017; Hill, 2018). Hill (2018) reported that living near shale gas wells development (1.5 miles) increased the prevalence of Apgar scores less than 8 by 26%, Casey et al. (2015) reported that exposure to the highest quartile of the activity index was associated with increased odds of high-risk pregnancy (ORs 1.3,95% CI: 1.1, 1.7) compared to the lowest quartile, and Currie et al. (2017) reported increased odds for index of infant health similar to the associations reported for LBW and birth weight. In addition, Busby & Mangano (Busby and Mangano, 2017) reported that in the counties with UOG wells there was a significant increase in infant mortality rates compared to counties without UOG (Rate Ratio (RR): 1.29; 95% CI: 1.05, 1.55). Casey et al. (2019) reported that living in the highest quartile of conventional and unconventional oil and gas activity versus quartiles 1–3 would increase the incidence of antenatal anxiety or depression (4.3 additional cases per 100 women, 95% CI: 1.5, 7.0). This risk difference appeared larger among mothers receiving Medical Assistance, an indicator of low family income (5.6 additional cases per 100 women, 95% CI: 0.5, 10.6). This study is the first study that evaluated psychological outcomes based on clinical diagnosis and the results are coherent with the associations reported for the general population in the self-reported studies.

To summarize, there is growing evidence to suggest that living near UOG development increases the risk for adverse pregnancy outcomes. For fetal growth, four out of seven studies reported significant robust associations (Casey et al., 2015; Currie et al., 2017; Hill, 2018; Stacy et al., 2015) and for PTD five out of seven studies reported statistically significant associations (Casey et al., 2019, 2015; Hill, 2018; Walker Whitworth et al., 2018; Whitworth et al., 2017). For other outcomes the results are less clear and further research is needed.

3.3.2. UOG exposure, hospitalizations, asthma exacerbations, and indicators of cardiovascular disease

Seven studies evaluated the associations between UOG development on hospitalization rates, a single study evaluated asthma exacerbations and a single study evaluated indicator of cardiovascular disease (Table 2). Jemielita et al. (2015), Denham et al. (2019) and Werner et al. (Werner et al., 2017, 2018, 2015) were exploratory studies that evaluated associations between UOG development and 25, 17, and 19 medical categories of hospitalization, respectively. Jemielita et al. (2015) reported, for most of the outcomes tested, increased prevalence rates, and significant associations (after using a Bonferroni correction) were reported for cardiology prevalence rates and the number of wells and wells density per zip code, and for neurology inpatient prevalence rates and wells density. Furthermore, evidence also supported an association between well density and inpatient prevalence rates for the medical categories of dermatology, neurology, oncology, and urology. Most of the UOG wells started to operate in the last year of the study. Denham et al. (2019) reported significant associations (accounting for multiple test) between cumulative well density (per km^2) and cumulative well count per county and increased genitourinary hospitalization rates. When large metropolitan counties were excluded these associations persisted, and associations with increased skin-related hospitalization rates were also reported. In three studies conducted in Queensland, Australia, the associations between hospitalization rates of 19 medical categories and three types of areas (coal seam gas area, coal mining area and rural/agricultural area) were evaluated for all ages and for children and adolescents. In addition, associations between hospitalizations rates and the number of coal seam gas wells in statistical areas were evaluated (Werner et al., 2017, 2018, 2015). The coal seam gas area correlated with an increase in hospitalization rates compared to rural areas for neoplasms (RR: 1.09, 95% CI: 1.02–1.16) and blood/ immune diseases (RR: 1.14, 95% CI: 1.02–1.27) (Werner et al., 2015). In a study of the same population, focusing on hospital admissions of children and adolescents, evidence for associations with respiratory diseases for children at ages 0–4 years old were found (7% increase (95% CI: 4%–11%) for coal seam gas area relative to the coal mining, and a 6% increase (95% CI:2%–10%) for coal seam gas area relative to rural areas). For children between the ages 10–14 years old the results were a 9% increase (95% CI: 1%–18%) for coal seam gas area relative to coal mining, and an 11% increase (95% CI: 1%–21%) for coal seam gas area relative to rural areas. The largest effect size was found for blood/immune diseases in 5–9 years old children living in coal seam gas areas (467% increase, 95% CI: 139%–1244%) relative to those living in rural areas with no mining activity (Werner et al., 2018). In addition, Werner et al. (2017) reported that "All-cause" hospitalization rates increased monotonically with increasing gas well development activity in females (from 324.0 to 390.3 per 1000 persons) and males (from 294.2 to 335.4 per 1000 persons). Inverse associations were found for both sexes for "circulatory" conditions (Table 2). It is important to note that while Jemielita et al. (2015) reported significant associations after Bonferroni corrections, Werner et al. (Werner et al., 2017, 2018, 2015) had not used any correction for multiple testing.

Two studies calculated changes in trends of hospitalization rates before and after drilling at the county and the zip code levels: Willis et al. (2018) investigated hospitalization due to pediatric asthma and Peng et al. (2018) investigated hospitalization due to acute myocardial infarction, chronic obstructive pulmonary disease, asthma, pneumonia, and upper respiratory infections. Willis et al. (2018) reported significant increased odds of an asthma-related hospitalization for adolescents exposed to newly spudded UOG wells within their zip code (OR: 1.25, 95% CI: 1.07, 1.47), compared with those who did not live in these communities. Ages 2–6 years had the greatest odds (OR: 1.44; 95% CI: 1.18, 1.75) followed by ages 13–18 (OR: 1.34, 95% CI: 1.13, 1.60). Willis et al. (2018) reported similar results also for ever-drilled UOG well within a zip code. The effect of exposure to the highest tertile of additional wells was associated with increased odds for all age groups (OR: 1.39, 95% CI: 1.14, 1.71), and in particular for ages 2–6 years (OR: 1.9, 95% CI: 1.34, 2.23). Whereas Peng et al. (2018) did not find similar effects of UOG development on asthma among children aged 5–19, they reported a significant increase in hospitalization rates for pneumonia among individuals aged 65 and above. Although associations were reported between UOG development and extraction and acute myocardial infarction, chronic obstructive pulmonary disease, asthma, and upper respiratory infections, these associations were sensitive to the method, as well as to the specifications of the models. The differences between Peng et al. (2018) and Willis et al. (2018) for asthma hospitalizations of children can be partly explained by the aggregation unit size. Namely, while Willis et al. (2018) studied associations at the zip code level, Peng et al. (2018) evaluated associations at the county unit, a much larger geographical unit, which may cause an aggregation bias that may lead to bias in the associations towards the null (Shafran-Nathan et al., 2017).

In addition to hospitalizations, a single study evaluated asthma exacerbations severity (mild, moderate, and severe, see Table 2) among asthma patients aged 5–90 (Rasmussen et al., 2016). Exposure to the highest quartile of the activity metric for each of the different UOG phases (pad preparation, drilling, stimulation and production) compared to the lowest increased the risk for 11 out of the 12 UOG-outcome pairs (OR ranged from 1.5 (95% CI: 1.2, 1.7) for the association of the pad metric with severe exacerbations to 4.4 (95% CI: 3.8, 5.2) for the association of the production metric with mild exacerbations). Six of the 12 UOG-outcome associations had increasing ORs across quartiles. The findings were robust to adjustment and to sensitivity analyses that included evaluation of some possible sources of unmeasured confounding.

Additionally, McKenzie et al. (2019b) evaluated in a cross-sectional study the associations between participant's exposure to combined conventional and unconventional oil and gas activity within 16 km from home and personal measures of cardiovascular disease indicators. Exposure to the highest and medium tertiles of the intensity of combined conventional and unconventional oil and gas activity level compared to the lowest increased the mean augmentation index by 6.0% (95% CI: 0.6, 11.4%) and 5.1% (95%CI: −0.1, 10.4%), respectively. The greatest mean IL-1β, and α-TNF plasma concentrations were observed for participants in the highest exposure tertile. For participants not taking prescription medications, exposure to the highest and medium tertiles compared to the lowest increased the mean systolic blood pressure by 6 and 1 mm Hg (95% CIs: 0.1, 13 mm Hg and −6, 8 mm Hg).

3.3.3. UOG exposure and cancer

The UOG process is known to utilize and produce numerous carcinogenic and leukemogenic compounds (Elliott et al., 2017). However, cancer can be an elusive disease to detect and monitor due to its rarity, relatively long etiologically relevant time periods, and latency periods. Since UOG development has rapidly expanded only after 2005 (Fukui et al., 2017), it is not surprising that only three epidemiological studies examined associations between UOG development and cancer incidence, two of which applied an ecologic study design (Table 3). Fryzek et al. (2013) calculated Standardized Incidence Ratios (SIRs) and 95% CIs at the county levels in Pennsylvania from 1990 through 2009 for childhood cancers. The first horizontal well in this study area in Pennsylvania was drilled only in 2005 and most of the horizontal wells were drilled after 2009. Therefore, studying the incidences of cancer from 1990 through 2009 is considered very unreliable, due to the limited latency period (even for childhood cancer). Fryzek et al. (2013) (with 97.5% of wells being non-horizontal [a proxy for non-UOG] wells) reported that for horizontal wells, the change in the SIRs for children (under the age of 20), for all cancers, leukemia, and central nervous system cancers, between the post-UOG period compared to the pre-UOG period, were non-significant. A critical response to this study highlighted its methodological shortcomings (Goldstein and Malone, 2013). Finkel, (2016) (Finkel, 2016) conducted an ecological study for a range of cancers at all ages in southwestern Pennsylvania and reported that for all ages, the SIR of urinary bladder cancer during 2008–2012, relative to 2000–2004, increased in both sexes in counties with UOG activity. Only a single study applied a case-control design (McKenzie et al., 2017) and examined children diagnosed with cancer (who lived in rural Colorado between 2001 and 2013). Childhood acute lymphocytic leukemia cases and non-Hodgkin lymphoma (NHL) cases were compared to controls with non-hematologic cancer participants. For each participant, exposure was estimated in terms of the number of conventional and UOG wells within a 10-mile radius from the residence address at diagnosis, for each year, during a 10-year latency period. For acute lymphocytic leukemia, cases of ages 5–24 were 4.3 times as likely to live in the highest tertile compared to controls (95% CI: 1.1 to 16), with a monotonic increase in risk across the tertiles. Further adjustment for the year of diagnosis increased the associations. While this study benefited from the ability to select cases and controls from the same population, the use of cancer-controls, the limited number of acute lymphocytic leukemia and NHL cases, and the aggregation of ages into five year intervals may have biased the associations toward the null.

To summarize, the reported associations of UOG with cancer are inconclusive, though the study with the strongest design suggested an association between oil and gas development and childhood cancers. Further studies accounting for longer latency periods and having strong study designs are needed.

3.3.4. UOG exposure and sexually transmitted diseases (STD)

Three studies evaluated the associations between UOG development and STD (Table 4). These studies hypothesize that increases in community-level STD rates are associated with the large influx of usually temporary young male workers needed to construct the well pad and initiate the drilling and fracturing processes, a relationship previously observed for other resource extraction industries. All the studies investigated gonorrhea, two studies also investigated chlamydia, and one study also investigated syphilis (Table 4). Komarek and Cseh (2017) compared the changes in gonorrhea incidence in counties with UOG and without UOG and also the associations with additional horizontal wells in parts of US states situated above the Marcellus Shale. In high UOG counties compared to the reference counties, a 20% statistically significant increase in gonorrhea incidence was reported. The associations were consistent across different model specifications. Deziel et al. (2018) examined the associations between UOG activity and the annual incidence rate of gonorrhea, chlamydia and syphilis in each year by a county in the state of Ohio. Compared to counties with no shale gas activity, counties with high activity had 21% (RR:1.21; 95%CI: 1.08, 1.36) increased rates of chlamydia and non-significant 19% (RR: 1.27; 95%CI: 0.98, 1.44) increased rates of gonorrhea; no associations were observed for syphilis. Beleche and Cintina (2018) examined the associations between counties with and without conventional and unconventional oil and gas wells and reported significant 7.8% and 2.6% increase relative to the average gonorrhea and chlamydia rate, respectively.

3.3.5. UOG exposure and fatal and major injury truck and traffic accidents

Although three studies evaluated the associations between UOG and traffic accidents, only two studies evaluated direct health outcomes, namely the number of traffic accidents, fatal, and major injury accidents due to traffic and the number of multivehicle truck accidents with an injury (Table 5). (Blair et al., 2018) reported significant associations and that more wells are associated with an increase in number and a higher probability of accidents with multiple vehicles with an injury. Although heavily drilled counties experienced higher vehicle crash rates and higher heavy truck crash rates than control counties. Graham et al., (2015) (Graham et al., 2015) did not report any significant associations with fatal and major injury accidents.

3.4. Mediation of the observed associations between UOG exposure and health outcomes

The specific exposure pathways underlying the observed associations have yet to be elucidated. Casey and Schwartz (2016) used directed acyclic graphs (DAGs) to suggest complex pathways by which UOG development may affect birth outcomes, including social and environmental impacts (e.g. psychosocial stress, social changes, truck traffic, noise, air and water pollution) that operate at the individual and community levels. Recent studies have tried to examine the suggested pathways. While Peng et al. (2018) reported significant associations between UOG development and air pollution emissions, Willis et al. (2018) reported that, for the years 2011–2014, increased emissions of specific air pollutants from UOG sites were associated with increased odds of pediatric asthma hospitalizations (for all-ages models: 2,2,4-trimethylpentane, carbon dioxide, formaldehyde, nitrous oxide, volatile organic compounds, and x-hexane; for ages 2–6 also carbon monoxide, methane, nitrogen oxides, $PM_{2.5}$, PM_{10}, toluene, and xylenes). In addition, Busby & Mangano (Busby and Mangano, 2017) reported that there is some evidence that the associations observed for infant mortality at the county level were related to private water well density and/or environmental law violations. Casey et al., (2019) conducted mediation analysis to evaluate if the effects reported previously between UOG activity and PTD and mean term birth weight are mediated by maternal anxiety and depression status. Although anxiety and depression were associated with UOG activity, it was not a mediator (there were no association between PTD and the psychological outcomes).

In addition, there are a growing number of environmental monitoring studies investigating whether proximity to UOG development is associated with increased exposure to air pollutants, drinking water contamination, noise, and other environmental stressors (Elliott et al., 2018, 2017; Hays et al., 2017; Hays and Shonkoff, 2016b). Future epidemiological studies should consider the use of air and water quality measures in the full population or a subset; however, this is a challenging proposition as exposure measurements are not generally feasible to collect in large-scale epidemiologic studies and may not be representative of past exposures in retrospective studies. Additional incorporation of mediation analysis may also help to better explain the mechanisms that affect the associations reported in these studies.

3.5. Other aspects to be considered

For this review we excluded qualitative studies of self-reported symptoms, as we aimed to focus on studies that quantified the associations with UOG development using objective health outcomes. However, it is important to recognize the existing evidence in this field of research, which suggests that a range of adverse self-reported health outcomes are associated with UOG development. Generally, these studies reported increased rates of symptoms by residents living near UOG infrastructure including sleep disruption, respiratory symptoms, nose and throat irritation, eye irritation, headaches and fatigue, among others (Casey et al., 2018; Elliott et al., 2018; Ferrar et al., 2013; Rabinowitz et al., 2014; Saberi, 2013; Saberi et al., 2014; Shamasunder et al., 2018; Steinzor et al., 2013, 2012; Tustin et al., 2016; Weinberger et al., 2017). Several of these findings are consistent with the results of the studies we described. The self-reported studies can provide context for the studies that do not involve participant contact and can serve to generate research questions for future analyses. Although not within the scope of this review, studies of self-reported health symptoms may still be highly relevant and should be considered by policymakers when making decisions with regard to UOG development.

Experimental studies have assessed UOG-related chemicals and toxicity, providing evidence of biological plausibility of associations observed in epidemiologic studies. Collectively, these studies have reported a range of effects such as endocrine disruption in yeast and mammalian assays (Arcaro et al., 2001, 1999; Kassotis et al., 2016, 2014; Vrabie et al., 2010), adverse developmental and reproductive effects such as suppressed pituitary hormone activity (Kassotis et al., 2016), altered sex organ weight and function (Kassotis et al., 2016, 2015), altered behavior (Balise et al., 2019a, 2019b; Boulé et al., 2018;

Sapouckey et al., 2018), and immune dysregulation (Boulé et al., 2018) in mice. Results from these laboratory studies indicate prenatal and/or early life exposure to UOG development-related chemicals may lead to altered health outcomes for a variety of endpoints, contributing to the overall body of evidence.

3.6. Policy impact

Accounting for the knowledge gaps and inevitable uncertainties as well as the current body of evidence, some countries and US states have decided to ban or delay UOG development until more knowledge becomes available, while other states and nations have restricted UOG development based on concerns raised from existing data (e.g. Maryland, Vermont, and New York in US, Quebec in Canada, Victoria in Australia, Scotland, Ireland, Bulgaria, Holland, Germany and France) (UNEP, 2012; Watterson and Dinan, 2018). One legislative approach to mitigating potential risks is requiring certain setback distances (i.e., the distance between well heads and nearby residences, hospitals and schools). The required setback distances in the US range between 300 ft and 800 ft (90–245 m) across 33 countries (Hill, 2018). However, the epidemiological evidence gathered thus far shows detectable health effects in distances of up to 10 miles away. A panel of 18 public health experts (health care providers, public health practitioners, environmental advocates, and researchers/scientists) reached a consensus that setbacks smaller than 0.25 mile (402 m) should not be recommended but they did not reach a consensus on larger setback distances (Lewis et al., 2018). In addition, they reached consensus that additional setback distances should be established for vulnerable populations (children, neonates, fetuses, embryos, pregnant women, elderly individuals, those with pre-existing medical or psychological conditions, and those with pre-existing respiratory conditions) or vulnerable settings (schools, day care centers, hospitals, and long-term care facilities). Another analysis found that setback distances may need to be used in conjunction with pollution or engineering controls to achieve desired public health protections (Haley et al., 2016). Additional quantitative analysis of the rapidly evolving epidemiologic literature could inform more evidence-based setback distances.

4. Summary

This review found that 25 of 29 studies observed significant associations between exposure to UOG development and a range of adverse health outcomes. This review highlights the heterogeneity among studies with respect to study design, outcome of interest, and exposure assessment methodology. The use of exposure surrogates would generally be expected to lead to non-differential exposure misclassification, biasing results toward the null. The most-studied outcomes were adverse birth outcomes; the number of studies for other outcomes was limited. Though replication in other populations is important, current research points to a growing body of evidence of health problems in communities living near UOG sites. Many health outcomes may take years to emerge and to be analyzed with sufficient statistical power, partly due to latency periods. The need for more research need not be used as a barrier to implementing policies.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

Not applicable.

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Authors' contributions

NCD made substantial contributions to the acquisition and interpretation of data, revising the draft based on an updated literature review and reviewer comments, and gave final approval of the version to be published. EB made substantial contributions to the data and interpretation of data; was involved in drafting the manuscript and revising it critically for important intellectual content and gave his final approval of the version to be published. IG was involved in initiating the study, revising the manuscript critically for important intellectual content and gave the final approval of the version to be published. CJC was involved in revising the manuscript critically for important intellectual content and gave final approval of the version to be published. ZBI was involved in drafting the manuscript and revising it critically for important intellectual content and gave his final approval of the version to be published. DB was involved in revising the manuscript critically for important intellectual content and gave his final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content; and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. KAS initiated the study, performed the analysis, made substantial contributions to conception and design and acquisition and interpretation of data; led the writing of the first draft of the manuscript, revising it critically for important intellectual content, led the revisions of the manuscript, made substantial contributions to the acquisition of new data, interpretation of data, and analysis of data and gave final approval of this version and is accountable for all aspects of the work.

Declaration of competing interest

The authors declare that they have no competing interests.

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Exhibit 38.05

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Short communication

Distance decay gradients in hazardous air pollution concentrations around oil and natural gas facilities in the city of Los Angeles: A pilot study

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ABSTRACT

In this work, we investigate air pollutant distance decay gradients around an upstream oil and natural gas (ONG) facility located within a densely populated urban community in South Los Angeles. Despite the difficulties associated with interpreting air quality measurements in complex, multi-source urban environments, this pilot investigation was able to identify distance decay around the target ONG site and distinguish added air quality burden of several volatile organic compounds associated with ONG operations. Moving forward, we recommend additional research to better distinguish air quality contributions from ONG in urban environments.

1. Introduction

Upstream oil and natural gas (ONG) development – including oil, gas, and liquid gas hydrocarbons – has expanded rapidly across the United States over the past decade. While much of the focus has been on ONG drilling and production in rural regions, many facilities operate in densely-populated urban areas. Few studies have focused on emissions and the potential impact on human health in the State of California, where approximately 58,000 ONG wells (Czolowski et al., 2017) operate, many of which are located in the oil-dense Los Angeles area. Approximately 1.7 million individuals live within one mile (~1.61 km) of an active ONG well within the Los Angeles Basin (Shonkoff, Gautier (2015)). Research on air quality near upstream ONG operations reveal a potential for adverse health impacts, and a review of the current literature suggests an association between proximity from ONG site and potential health risks (Garcia-Gonzales et al., 2019). Most of these health studies, however, have failed to feature any rigorous spatial analysis of pollutant levels, only suggesting that a spatial dimension exists. Further limiting the understanding between ONG operations and health is California's unique geology which may limit the generalizability of study results collected in other states where research is more common.

Los Angeles residents already experience a high health burden from poor air quality, where exposure to urban air pollution, including traffic emissions, increases risk for multiple adverse health outcomes (Jerrett et al., 2005; Ghosh et al., 2013; Wilhelm et al., 2011). Studies have demonstrated gradient behavior in combustion-related emissions; pollutant levels are elevated near roadways and decrease to or near background levels as distance from the roadway increased, with some studies suggesting most of the human health impacts from combustion related exposures occur within 500 m of major highways (Beckerman et al., 2008; Hu et al., 2009; Zhu et al., 2006). Few studies have repeated this gradient monitoring approach around ONG facilities, despite the need to understand the behavior of related air emissions, especially those located within dense urban communities.

Given the sparse literature on exposures to air pollutants near ONG operations and the potential for impacts on health, particularly in urban areas where residents experience exposures from multiple sources, here we investigate air pollutant gradient behavior around an actively producing ONG facility located in South Los Angeles, a neighborhood identified as an "environmental justice" community by the State of California. The consequences of exposure to ONG-related emissions have not been adequately studied in a densely populated context, and thus, the investigations on distance decay behavior are needed to understand the risks associated with exposures from these activities, particularly in densely populated areas, to guide future regulation.

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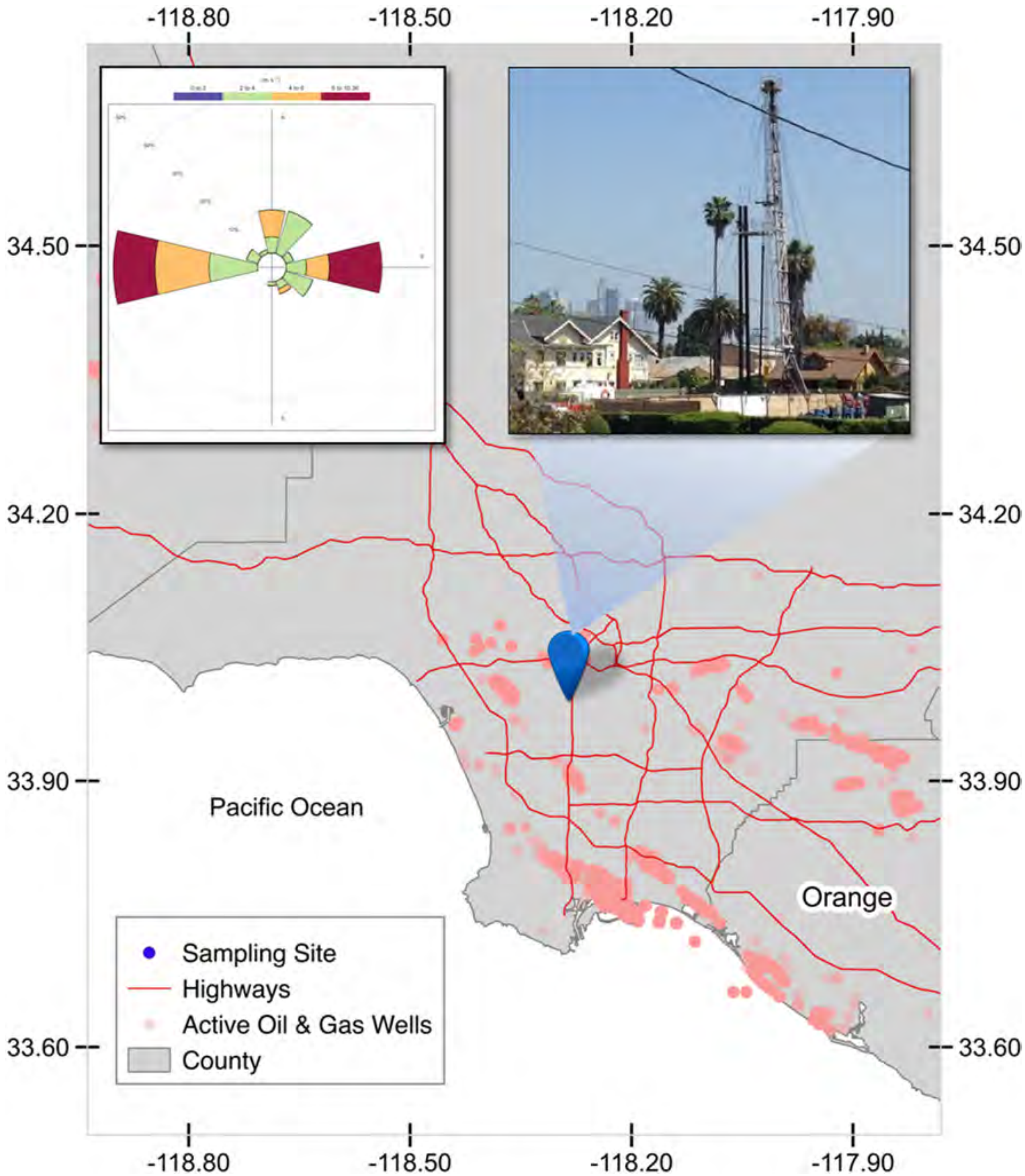

Fig. 1. Location of the Jefferson drill site in South Los Angeles with wind rose diagram for meteorological data collected February 17 – March 2, 2016. Geographic shapefiles are from the California Department of Transportation and the Division of Oil, Gas, and Geothermal Resources. Image is borrowed from Redeemer Community Partnership at www.redeemercp.org.

2. Materials and methods

2.1. Site selection

To understand the distance decay of ONG related emissions in Southern California's urban environment, a facility was selected near South Los Angeles, in the West Adams community. The Jefferson drill site is an actively producing ONG facility that has been in operation since 1964 and operates 20 active oil and gas wells with a total gas production of 8890 million cubic feet (Mcf) of natural gas and 8553 barrels (bbls) of oil in February 2016, the month of the current sampling deployment. According to U.S. Energy Information Administration's average daily oil and natural gas production volume per well for 2016, the Jefferson drill site is among the top 9% of gas producing and top 34% of oil producing wells in California (EIA, 2017).

The Jefferson drill site (Fig. 1) is situated in the middle of a disadvantaged community facing multiple adverse exposures, where wellheads are as close as 60 feet (~18 m) from residential homes, most in which predate the site. The Jefferson drill site is located due south of Interstate Highway 10 (~1.2 km) and west of Highway 110 (~2 km), each with 100,000s of vehicles per day, along a major bus route and is surrounded by a myriad of competing emissions sources including several restaurants, laundry mats, dry cleaners, a recycling center, and two gas stations (all within 1 km). The site was selected due to the high level of operational activity at the facility, residential proximity, the existence of an established neighborhood advocacy group that could facilitate community air monitoring, and the ability to create a distance decay gradient through the site along the prevailing wind directions. A

Table 1
Summary statistics for all passive TraceAir badges along the Jefferson drill site transect.

	Benzene	2-BE[e]	n-Hexane	n-Pentane
Descriptive Statistics				
LOD[a]	0.09	1.00	0.15	0.15
Mean RPD[b]	2.02	NA	1.23	4.35
Range	0.47–0.55	NA	0.40–0.50	0.89–1.30
Median	0.51	< 1.00	0.42	1.10
Mean	0.51	< 1.00	0.43	1.07
Comparison Values				
Control	0.51	< 1.00	0.39	0.99
Baker[c]	0.48	NA	0.39	1.20
MATES IV[d]	0.40	NA	NA	NA
Spearman Correlation				
Benzene	1	NA	0.90**	0.55
2-BE	NA	NA	NA	NA
n-Hexane	0.90**	NA	1	0.68
n-Pentane	0.55	NA	0.68	1

Data provided in ppbv. Non-detects are denoted by the "less than" sign, followed by the sample limit of detection.
*p-value < 0.1, **p-value < 0.01.
[a] Limit of detection (LOD) – calculated as the mean reporting limit for all samples along the transect for each measured analyte in ppbv.
[b] Mean Relative Percent Difference (RPD) between duplicate samples. All duplicates were under 10% RPD.
[c] Baker, A. K. et al. Measurements of nonmethane hydrocarbons in 28 United States cities. *Atmos. Environ.* 42, 170–182 (2008).
[d] MATES IV. Available at: http://www.aqmd.gov/home/air-quality/air-quality-studies/health-studies/mates-iv. (Accessed: 27th June 2018).
[e] 2-BE (2-Butoxyethanol).

total of 11 residential sampling sites were recruited to host air quality samplers for 14 days. Hosts were selected from non-smoking households and advised to avoid activities that may expose the monitors to additional VOC emissions including, but not limited to, burning firewood, barbeques, and the operation of yard equipment with combustion engines (e.g. gas-powered lawn mowers).

2.2. Passive TraceAir badges

Commercially available passive samplers do not require a power source and are generally inconspicuous when deployed. As such, these samplers can be utilized ubiquitously across multiple site locations in dense urban environments where security might be a concern. For this study, we used passive TraceAir badges model 521 (Assay Technology), which are capable of collecting a panel of organic air pollutants through passive diffusion in a time-integrated manner. We deployed 15 TraceAir passive badges around 11 residential locations near the Jefferson drill site. To protect the samplers from the elements, all passive badges were placed within an open bottom non-treated AllCan West (http://allstatecan.com/) tin can affixed to a metal fence post or existing structure at each site.

Three passive TraceAir badges were placed along the western transect and an additional six passive badges were placed along the eastern transect. In both directions, passive badges were placed up to ~245 m from the closest wellhead, over twice the distance previous research identified impacts in air quality near a similar facility (Zielinska et al., 2014). An additional passive badge was used as a control and placed at a residential home approximately 750 m northwest of the facility, away from the prevailing wind direction, and over 500 m away from any major highway. For quality assurance and control, the remaining passive badges were used as either field duplicates, field blanks, or travel blanks. Latitude and longitude coordinates were collected for each passive badge using a Garmin eTrek global positioning system (GPS) device.

Air toxics including benzene and n-hexane have been found at elevated concentrations and with stronger correlations to the ONG tracer compound, n-pentane, near upstream ONG operations in several peer-reviewed studies. Due to the importance of these three analytes in ONG operations, they were included among the sampled species. The toxic organic compound, 2-butoxyethanol, has been found in well water near ONG operations within the Marcellus Shale (Llewellyn et al., 2015), but was included among the list of sampled species due to increased community concerns of reported chemical usage at the Jefferson drill site. After 14 days of production-phase air quality sampling, badges were collected and sent to Assay Technology laboratories in Ohio for analysis of n-pentane (CAS 109-66-0), n-hexane (CAS 110-54-3), benzene (CAS 71-43-2), and 2-butoxyethanol (CAS 111-76-2). Passive badges were processed using a modified OSHA 7 method which included desorption in carbon disulfide with co-solvent and analysis by gas chromatography with flame ionization detector (GC/FID). Data was blank corrected and provided as average concentrations for the period of time monitored.

3. Results

3.1. Descriptive statistics

Of the 15 TraceAir samples collected, one was damaged and excluded from the analysis. Precision of duplicates was ≤10%, and the remaining field samples were blank corrected. Concentrations of benzene, n-hexane, and n-pentane were found above the sample limit of detection (LOD) in all deployed badges; 2-butoxyethanol was found under the sample LOD in every sample. Mean two-week time weighted average concentrations for benzene, n-hexane, and n-pentane were 0.51, 0.43, and 1.07 ppb, respectively. Concentrations of benzene and n-pentane at the control location were within the range of the samples included in the transect; the n-hexane concentration measured at the control site was lower than the range of the samples included in transect. Non-significant relationships were found between n-pentane and n-hexane ($r^2 = 0.68$, $p = 0.02$) and between n-pentane and benzene ($r^2 = 0.55$, p-value = 0.08); however, it is difficult to fully interpret the correlations between the HAPs and tracer compound due to the small sample size. Descriptive statistics and correlations can be viewed in Table 1.

3.2. Distance decay gradients

Passive TraceAir badges were deployed at increasing distances along the prevailing eastern and western wind transects. Wind data from MesoWest (Station ID: KCQT) was plotted in a 40-degree panel wind rose diagram for the two-week deployment timeframe (Fig. 1) revealing prevailing wind patterns from the western and eastern directions. Wind originating from the east and west contributed to 25% and 35% of the total mean wind patterns, respectively. Wind speeds in both directions ranged from 2 to 10.36 meters/second with 0% calm. All other wind directions contributed to ~10% or less of the total mean wind patterns for the sampling timeframe. With an exception of the control location, all sensors were placed along the two prevailing (eastern and western) wind transects.

Two-week time weighted concentrations for all VOC species were standardized using the maximum value of the respective VOC from the full transect in the denominator and presented as a percent of the maximum. Standardized results were plotted against distance in meters from the center of the targeted ONG facility in both directions. Fig. 2 represents a plot of the transect through the well pad and shows a decline in concentrations from the samples collected at the eastern fence line (quadrant 1), closest to the ONG facility, compared to the second sampling location 70 m in the eastern direction for all compounds over the sample limit of detection (LOD). Along the eastern transect, concentrations of benzene and n-hexane decayed to background at approximately 130 and 195 m, respectively, from the closest facility wellhead. Concentrations of n-pentane decayed to background levels at approximately 165 m from the closest wellhead, but

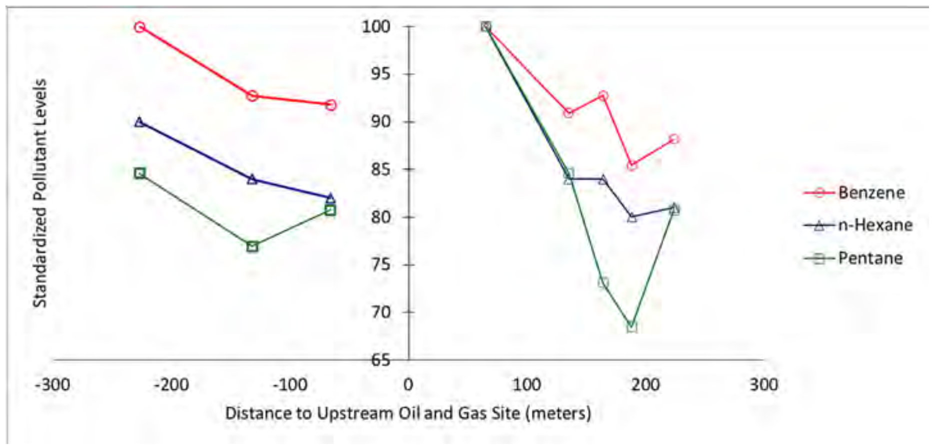

Fig. 2. Results of the distance decay gradient for data collected between February 17 – March 2, 2016.

concentrations increased at the furthest sampling location. Along the western transect (quadrant 2), n-pentane concentrations increased near the facility while both n-hexane and benzene levels increased as distance from the targeted facility increased.

4. Discussion

Passive samplers are inexpensive air quality sensors capable of measuring time-weighted average concentrations of a variety of VOCs in ambient conditions. The proven utility of passive samplers has been demonstrated in several ONG monitoring studies (Zielinska et al., 2014; Macey et al., 2014; Eisele et al., 2016), but these samplers have yet to be used around ONG facilities in dense, urban environments. Our results show that mean two-week time-weighted average concentrations of benzene and n-hexane from all transect samples exceeded those found in 28 cities (Baker et al., 2008) and in the recent Multiple Air Toxics Exposure Study (MATES) IV report (benzene only) on air quality where weekly samples were collected over 1 year at the Central Los Angeles South Coast Air Quality Management District sampling location (South Coast Air Quality M, 2015). Overall, however, concentrations were comparable to levels measured at the control site, located more than 750 m north of the facility and out of the path of the developed transect.

In urban environments, VOCs such as benzene, n-pentane, and n-hexane are predominately emitted from anthropogenic sources such as evaporating, unburned fuel. In Los Angeles, benzene, and to a lesser extent, n-pentane and n-hexane, are correlated with carbon monoxide, emitted via incomplete combustion, suggesting these VOCs share a common vehicle source (Baker et al., 2008). Therefore, it may be difficult to characterize ONG emissions in urban environments where competing emission sources are difficult to isolate. Further complicating these efforts is the distribution of existing architectural structures within this dense urban neighborhood that may distribute particles and other air toxics unequally throughout the community.

While we identify gradient behavior on the eastern transect, the western transect is likely influenced by a source upwind of the sampling locations. This probable upwind source is combustion emissions from the highly utilized four-lane road one block west of the furthest passive badge, as evident in the diffusion of benzene and n-hexane concentrations from the prevailing westerly winds. Similarly, concentrations measured downwind of the facility are likely influenced by multiple contributing sources including combustion emissions. Elevated concentrations between passive badge concentrations deployed at the eastern and western fence lines; however, followed by decreasing concentrations with increasing distance from the facility provide insights into the added pollutant burden which, from our analysis, increased 9%, 22%, and 24% for benzene, n-hexane, and n-pentane, respectively, along the eastern transect.

Using a distance-decay gradient, a previous study in the semi-rural region of the Barnett Shale, Texas, found that measured VOCs decayed to background concentration within 100 m of ONG facilities (Zielinska et al., 2014). Along the eastern transect of our current study, benzene showed similar decay patterns, but n-hexane displayed a higher impact from the facility with elevated concentrations above background close to 200 m from the closest wellhead. Concentrations of n-pentane follow the expected decay patterns better along the eastern transect compared to the western transect, where the major contribution to measured VOCs is likely from vehicle emissions. On the eastern transect, n-pentane showed decreasing concentrations until the final sampler where concentrations rise likely due to an additional local n-pentane source.

5. Conclusion

Despite the presence of multiple contributing sources and the difficulties associated with deployment in dense urban environments, we were able to identify gradient behavior along the transect downwind of the target ONG facility that was likely due, in part, to emissions from the facility; identify a possible correlation between target VOCs with the natural gas tracer compound, n-pentane; and identify added air quality exposure burden from the targeted ONG facility. Further, distance decay studies in complex urban environments such as Los Angeles County, where large populations could be adversely affected by elevated levels of hazardous air pollutants, are warranted - especially since the unique geology of California's shale merits site specific research in order to better understand whether and how results from other regions may be generalizable to Los Angeles. Such studies should preferably use monitors capable of determining temporal patterns of exposure as a compliment to contributions of ONG to observed spatial gradients to elucidate the full range of potential health impacts.

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Exhibit 38.06

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Review

Impact of upstream oil extraction and environmental public health: A review of the evidence

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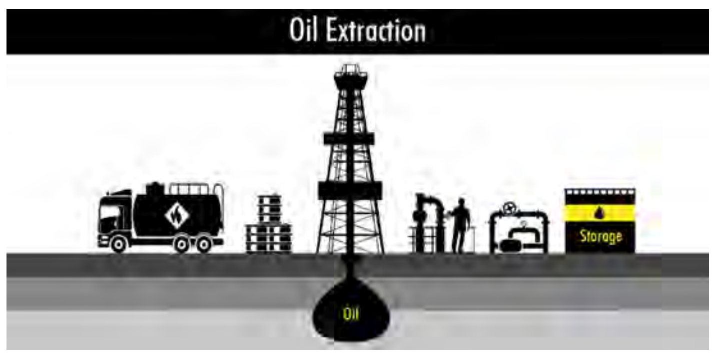
HIGHLIGHTS

- Identifies 63 studies on the exposure and health risks related to oil extraction
- Examines the human health effects of oil drilling
- Discusses potential exposure pathways via include air, soil, water and waste fluids

GRAPHICAL ABSTRACT



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ABSTRACT

Upstream oil extraction, which includes exploration and operation to bring crude oil to the surface, frequently occurs near human populations. There are approximately 40,000 oil fields globally and 6 million people that live or work nearby. Oil extraction can impact local soil, water, and air, which in turn can influence community health. As oil resources are increasingly being extracted near human populations, we highlight the current scope of scientific knowledge regarding potential community health impacts with the aim to help identify scientific gaps and inform policy discussions surrounding oil drilling operations. In this review, we assess the wide range of both direct and indirect impacts that oil drilling operations can have on human health, with specific emphasis on understanding the body of scientific literature to assess potential environmental and health risks to residents living near active onshore oil extraction sites. From an initial literature search capturing 2236 studies, we identified 22 human studies, including 5 occupational studies, 5 animal studies, 6 experimental studies and 31 oil drilling-related exposure studies relevant to the scope of this review. The current evidence suggests potential health impacts due to exposure to upstream oil extraction, such as cancer, liver damage, immunodeficiency, and neurological symptoms. Adverse impacts to soil, air, and water quality in oil drilling regions were also identified. Improved characterization of exposures by community health studies and further study of the chemical mixtures associated with oil extraction will be critical to determining the full range of health risks to communities living near oil extraction.

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Contents

1. Introduction

Modern oil extraction frequently occurs near human populations. Globally, there are an estimated 70,000 oil fields across ~100 countries with over 1600 billion barrels of known crude oil reservoirs (CIA, 2017; Bentley, 2002; Mead, 1993). Existing oil fields have been estimated to potentially impact the health and environment of over 600 million people worldwide (O'Callaghan-Gordo et al., 2016). In the United States, the doubling of oil production in less than a decade and growth of new oil wells has raised new and longstanding public concerns about the health and safety of these nearby populations (EIA, 2018; Tadeo, 2017). Of the approximately 808,485 active oil wells located in the continental United States (US), an estimated 8 million people live near (<1600 m) an active oil extraction site (Czolowski et al., 2017).

Oil forms in sedimentary rocks 2 to 4 km below the surface where there are high enough pressures and temperatures to transform organic matter into liquid hydrocarbons through thermogenic breakdown (J. Li et al., 2016). Oil exploration, drilling, and extraction are the first phase—or the "upstream" phase—in the lifecycle of oil. Once an oil resource is identified, a single well typically operates for 20–30 years, with the region being occupied for multiple decades with associated activities such as construction, production, processing, and transportation. As oil extraction is becoming more common near where people live, work and play, such activities have the potential to affect public health.

While there have been recent epidemiological studies and scientific reviews on the environmental and human health risks related to unconventional natural gas extraction in the United States (Adgate et al., 2014; Saunders et al., 2016; Shonkoff et al., 2014), there is a lack of systematic analyses of the environmental or health impacts from oil exploration, drilling, and extraction (Lave and Lutz, 2014). Various health impacts among exposed residents and cleanup workers of several large oil tanker or offshore oil spills have previously been reviewed with respect to acute physical, psychologic, genotoxic, and endocrine effects (Aguilera et al., 2010). The potential health impacts among residents living close to oil fields and potentially exposed for long periods of time have received less attention. In this review, we leverage existing scientific literature to assess the potential range of both direct and indirect impacts that oil drilling operations can have on local communities, with specific emphasis on understanding the body of scientific literature to assess potential environmental and health risks to residents living near oil extraction sites.

2. Methods

2.1. Scope of review

The production chain of oil development involves multiple steps, ranging from extraction to transportation, refinement, and combustion. For purposes of this review, we focused on the health implications of processes that happen upstream, that is, on-site at the well production pad or field, a current focus of public health policy and community concern (McKenzie et al., 2016). Studies with an experimental design, with measurements of exposures or health outcomes, were considered. In addition, we included toxicological or animal studies directly assessing potential ecological or health-related impacts of oil drilling activities or studies employing risk assessment models estimating a health-related outcome based on measured exposure data. Occupational studies were eligible only if they covered onshore workers and addressed an environmental hazard.

2.2. Identification of relevant studies

Existing literature that is relevant to oil extraction, either using conventional or unconventional techniques, remains limited. We employed a broad search strategy using multiple databases including: Web of Science- Biosis Citation Index, Ovid- Global Health, EBSCO Host-Greenfile and Environment Index, EMBASE, and PubMed. In addition, we completed manual searches of references related to oil development from included peer-reviewed studies. No date restrictions were placed, and the last date of a search was on April 14, 2017.

We developed the search terms and identified databases most likely to hold studies applicable to our topic of review. Search terms used were similar for all databases except for the sub-database Global Health for

Ovid, with terms including variations of oil drilling: (oilfield OR oil field OR petroleum extraction OR fossil fuel extraction OR oil drilling) AND (health OR disease) AND (human), to focus on human health effects. Global Health used slightly altered terms: (oil and gas industry OR petroleum industry) AND (oilfield OR oil drill OR petroleum drill) AND (health OR epidemiology).

2.3. Study selection criteria

Our primary interest was the identification of literature focused on chemical or health impacts of oil drilling and/or oil extraction. We focused on exposure pathways of greatest relevance to human health (e.g. air, water, soil) or epidemiological studies that included some metric for exposure to oil wells. We also included studies of animals (field-based and toxicological) directly related to oil drilling. Studies dealing with only natural gas extraction operations were not considered appropriate for this review and have been summarized elsewhere (Shonkoff et al., 2014). Further, we restricted the review to onshore (rather than offshore or ocean-based) drilling operations, as occupational health risks to off-shore workers have previously been reviewed (Gardner, 2003). However, occupational studies were included if they were specific to upstream oil workers and assessed an environmental hazard. That is, studies that focused only on mechanical occupational hazards, such as repetitive stress injury or work patterns, were excluded. Commentaries and publications that reviewed existing literature were also excluded, but their reference lists were examined.

Abstracts and selected full-texts for each study were screened based on the eligibility criteria stated above, with two independent reviewers determining whether the study merited final inclusion. Any discrepancies during the screening phase were resolved by consensus through discussions between the two reviewers. All studies selected for review needed to have full-text available in either English or Spanish. Each full-text was first evaluated by one reviewer (EL) and extracted for information on study design, methodology, affected population, route of exposure, (health) effect, magnitude of effect, and country of study. A table of this information was then reviewed by the second reviewer (JJ). During this process, missing information was supplemented, and incorrect information was marked with corrections. Afterwards, all changes were discussed between the two reviewers to reach consensus for inclusion in the final literature for review.

Quality assessments of individual studies were determined and labeled as either inadequate, fair, or good. A study meriting an "inadequate" rating had significant methodological faults or was unclear with details or rationale behind its methodological structure. In contrast, studies with a clear methodology, use of standardized measures, and a systematic collection of data were graded as "fair." Conclusions also had to be supported by the results. Furthermore, "good" ratings were reserved for studies which, in addition to all the qualities of a "fair" study, also directly observed the relationship between oil drilling and human health, clearly defined the study design and measure, and conducted robust and appropriate statistical analyses. Overall, information on funding sources was also assessed and recorded to identify possible biases afforded by the study team and the research outcomes presented in the text.

3. Results

3.1. Study selection & characteristics

After screening (n = 2236) and full-text review (n = 214), 63 original peer-reviewed articles published between 1993 and 2017 were selected for inclusion in the qualitative synthesis (Fig. 1). Each study was summarized by population, study design, exposure metric, health outcome, results, and quality (Table 1). This set of literature is international in scope with 20 countries represented: Australia (1), Bolivia (1), China (8), Colombia (1), Ecuador (9), India (1), Iran (1), Iraq (1), Italy (1), Kazakhstan (2), Kuwait (2), Nigeria (10), Oman (1), Peru (2), Russia (2), Trinidad and Tobago (1), Tunisia (1), and US (17) (Fig. 2). Studies were identified as belonging in one of four broad categories: human health and community well-being (n = 22), animal biomonitoring (n = 5), exposure assessment (n = 30), and experimental/toxicological (n = 6). Furthermore, human health and well-being studies were divided into occupational and non-occupational studies, while subcategories of environmental exposure pathways included air, soil, water, and waste products. Studies were included in more than one category if applicable.

3.2. Population health and oil extraction

3.2.1. Community health

Of the studies reviewed, we identified 15 studies that used epidemiological methods to assess health outcomes from non-occupational exposures associated with oil drilling (Table 1). The scope of health endpoints investigated varied substantially from chronic diseases to acute symptoms, including cancer, hospitalizations, liver damage, autoimmune disorders, allergies, respiratory symptoms, general well-being, and quality of life.

3.2.1.1. Cancer. Six studies assessed the association between cancer and oil extraction, the majority of which were based in the Amazon region of Ecuador. Comparing cancer incidence in a small Ecuadorian community in the Amazon basin impacted by oil extraction to a reference population, San Sebastián and colleagues found an excess of incidence and mortality for all types of cancer (San Sebastián et al., 2001b). A subsequent study of 4 counties with at least 20 years of oil extraction also showed excess risk for cancer incidence, including an increase in childhood hematopoietic (blood stem cell) cancer (Hurtig and San Sebastian, 2002). The same authors also identified a significantly elevated relative risk for leukemia (RR 3.48, 95% CI 1.25–9.67) among Ecuadorian children <14 years of age who lived in an oil extraction region compared to those who did not (Hurtig and San Sebastian, 2004). In the US, a Colorado registry-based case-control study found that children (ages 5–24) diagnosed with acute lymphocytic leukemia were 4.3 times as likely as controls (children with non-hematologic cancers) to live near active oil and gas extraction wells (McKenzie et al., 2017). In this study, authors show a positive association even after adjusting for age, race, gender, socioeconomic status, and elevation, but did not distinguish between oil and gas extraction wells. However, other analyses did not observe a significant relationship between oil production and cancer mortality. In Ecuador, researchers relying on a national mortality dataset found comparable county-level cancer mortality rates between oil producing and non-oil producing regions (Kelsh et al., 2009). Another analysis of cancer mortality in Ecuador, funded in part by the Chevron Corporation, saw no difference in rates between oil-producing and other regions of the country even while incorporating oil production data (Moolgavkar et al., 2014). The studies with null findings regarding cancer and oil production relied on all-cause mortality datasets and did not look at incidence or prevalence data. In all cases, the reliance on datasets with incomplete information (such as the exact address or date of diagnoses) and missing cases may influence study findings.

3.2.1.2. Acute and non-cancer health outcomes. Several studies identified multiple acute and chronic non-cancer health effects elevated in communities living near oil extraction, typically relying on a cross-sectional design. A study of a New Mexico community near an oil drilling site and an oil waste pit identified elevated prevalence of rheumatic disease, lupus, neurological and respiratory symptoms, and cardiovascular problems compared to a community farther away (Dahlgren et al., 2007). Multiple studies have found suggested evidence of alteration of immunological function in communities near oil extraction which may explain higher rates of lupus (Dahlgren et al., 2007), liver abnormality (Dey et al., 2015) and allergic disease (Yermukhanova et al.,

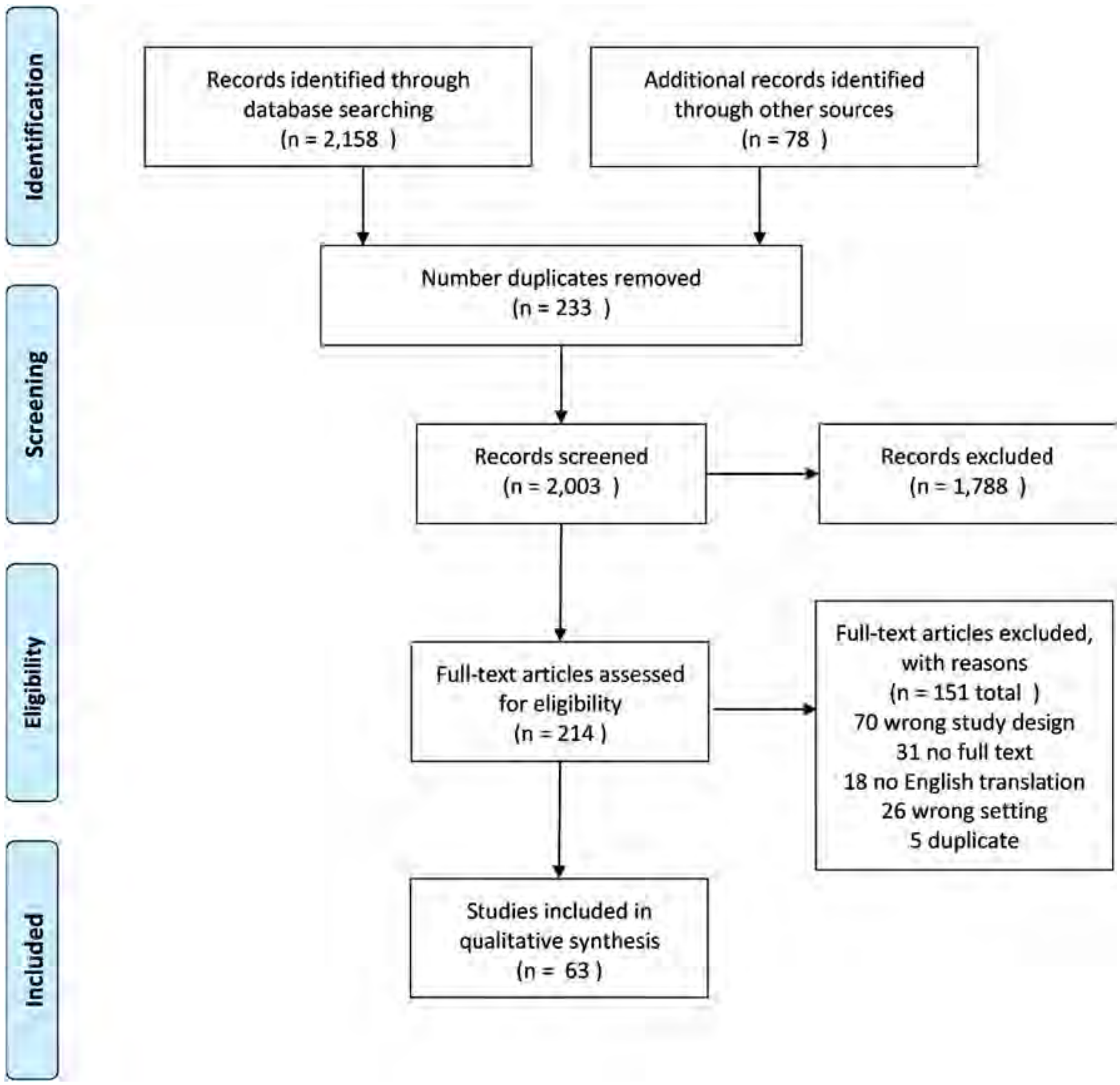

Fig. 1. PRISMA diagram with levels of screening and selection of literature at each stage.

2017). Adults living within 5 km of an oil field had significantly lower levels of 3 liver enzymes—alanine transaminase, aspartate transaminase, and alkaline phosphatase—as measured in blood when compared to adults living in a non-industrial region without oil drilling sites (Dey et al., 2015). School-age children (ages 7–11) in the oil-producing region in Kazakhstan found significant enlargement of thyroid volume in children living in the oil-producing regions, compared to those living in agricultural regions (Kudabayeva et al., 2014) and presence of allergic disease decreased with distance from the oil fields (Yermukhanova et al., 2017). All studies suggest that exposure to oil-related air pollutants may be adversely impacting immunological functions and driving the observed health differences.

A comparative study using a structured questionnaire among women living near oil wells in Ecuador identified higher prevalence of skin fungi, nasal irritation, and throat irritation (San Sebastián et al., 2001a). A similarly designed questionnaire based study in rural Nigeria found significantly higher rates of neurological symptoms, including headache, dizziness, eye and skin irritation, and anemia after adjusting for age, sex, and smoking status (Kponee et al., 2015). No difference was found between communities for gastrointestinal symptoms, malaria, or general pain metrics. Using hospital records, numerous cases of asthma, bronchitis, eye, and skin infection were identified in 9 rural Nigerian communities near oil fields, although there was not a clear analysis of the association between exposure and hospital data, nor were these rates compared to an unexposed population (Ogbija et al., 2015). 95.2% of the participants reported experiencing environmental degradation of air, water, or land due to oil drilling operations, identifying oil spills and air pollution from flaring as important risk factors to environmental health (Ogbija et al., 2015).

Contamination of water has been identified as another possible mechanism for observations of health risks. Women relying on surface water for household needs and men working in oil spill remediation recorded the highest levels of urinary mercury in oil extraction regions of Ecuador and Peru (Webb et al., 2016). Overall, however, the urinary mercury levels in this population were consistent with global background levels, while 7% of participants exceeded World Health Organization background levels.

Only one study was found examining birth outcomes in relation to oil extraction. After adjusting for socioeconomic factors, women of child-bearing age from exposed communities reported higher numbers of spontaneous abortions (OR: 2.47, 95% CI 1.61–3.79); however, no significant differences in stillbirth were observed (San Sebastian et al., 2002). This review did not identify any studies assessing birth outcomes, such as birth weight, pre-term birth, or birth defects.

Table 1
Summary of epidemiological studies on health outcomes from exposures associated with oil drilling.

Author(s)	Year	Country	Study design	Study population and sample size (n)	Findings	Health effect	Quality
Cancer							
San Sebastian et al.	2001	Ecuador	Cross-sectional	10 cases from ~1000 residents in San Carlos, 1989–98	Village near oil fields had to 3.6 times higher cancer incidence and mortality among males	Effect	Good
Hurtig and San Sebastian	2002	Ecuador	Cross-sectional	Cancer cases n in 4 exposed (n = 473) vs 11 unexposed (n = 512) counties, 1985–1998	Significant increase in incidence of (1) stomach, rectum, skin, soft tissue, and kidney cancer for men, (2) cervical and lymph cancer for women, and (3) hematopoietic cancers for children <10 in oil exploration regions	Effect	Good
Hurtig and San Sebastian	2004	Ecuador	Cross-sectional	91 cancer cases, 1985–2000	Significantly elevated risk of leukemia among children <14 years living in an oil extraction region	Effect	Good
Kelsh et al.	2009	Ecuador	Ecological	7713 deaths (of 2,569,685 person-years) in exposed vs 7622 deaths (of 2,428,113 person-years) in unexposed regions, 1990–2005	No significant increase in county-level cancer mortality rates in oil producing regions	No effect	
Moolgavkar et al.	2014	Ecuador	Ecological	Population and mortality data, 1990–2010	No significant difference in cancer mortality rates between oil-producing and non-oil producing areas	No effect	Fair
McKenzie et al.	2017	United States	Case-control	743 children (ages 0–24) with hematologic cancers vs non-hematologic cancers, 2001–2013	Children ages 5–24 with acute lymphocytic leukemia were 4.3 times more likely to live in an area with the highest concentration of oil and gas wells	Effect	Good
Birth & reproductive outcomes							
San Sebastian et al.	2002	Ecuador	Cross-sectional	365 exposed compared to 283 non-exposed women (ages 17–45), 1998–99	Increased likelihood of pregnancy resulting in spontaneous abortion among women in exposed communities	Effect	Good
Acute & non-cancer outcomes							
San Sebastian et al.	2001	Ecuador	Cross-sectional	368 exposed compared to 291 in non-exposed communities between 1998 and 99	Exposed women had significantly higher prevalence of nose and throat irritation. Headaches, earaches, eye irritation, diarrhea, and gastritis associated with nearness to oil wells.	Effect	Good
Dahlgren et al.	2007	United States	Cross-sectional	90 exposed vs 129 unexposed adults	Higher prevalence of rheumatic diseases, lupus, neurological symptoms, respiratory symptoms, and cardiovascular problems	Effect	Good
Kudabayeva et al.	2014	Kazakhstan	Cross-sectional	368 exposed children vs 447 unexposed	Higher prevalence of goiter in children ages 7–11 living in oil-producing regions	Effect	Fair
Dey et al.	2015	India	Cross-sectional	46 exposed vs 61 control participants	Higher levels of respirable PM and NO2 associated with long-term liver injury in exposed group	Effect	Good
Kponee et al.	2015	Nigeria	Cross-sectional	100 exposed vs 100 unexposed adults	Increased reports of neurological and hematological health problems among exposed residents	Effect	Good
Ogbija et al.	2015	Nigeria	Cross-sectional	373 participants living in oil-producing communities	Household survey to assess perception of environmental degradation and enumerate cases of diarrhea, asthma, skin infection and bronchitis.	–	Inadequate
Webb et al.	2016	Peru	Cross-sectional	76 participants (ages 15 and older)	No significant increase in mercury levels in urine in populations living near oil extraction sites.	No effect	Fair
Yermukhanova et al.	2017	Kazakhstan	Cross-sectional	424 participants with immuno-deficiency syndrome (stages 2 and 3)	Decrease prevalence of immunodeficiency decreased with increasing distance from oil fields	Effect	Fair
Occupational health studies							
Esswein et al.	2013	United States	Cross-sectional	111 personal breathing zone samples from workers in 5 states	Silica levels of hydraulic fracturing oil workers were ~10 times higher than recommended levels	Effect	Good
Gun et al.	2004	Australia	Cohort	708 Australian petroleum industry employee deaths of 17,165 persons, 1981–96	No significant increase in cancer mortality among cohort of workers in petroleum industry	No effect	Good
Kilburn	1993	United States	Case study	24-year old oil well tester exposed to 14,000 ppm hydrogen sulfide gas	Persistent and severe neurobehavioral symptoms after acute hydrogen sulfide gas exposure	Effect	Fair
Mousa	2015	Not specified	Observational	34 male patients (ages 22–60) attending an oil field clinic, 2012–13	Oil field workers exposed to subchronic low levels of hydrogen sulfide reported upper respiratory tract bleeding	Effect	Inadequate
Paz-y-Miño et al.	2008	Ecuador	Cross-sectional	46 oil workers exposed to hydrocarbons vs 46 non-exposed	Increased risk of mutagenic and carcinogenic damage and increased symptoms of common illnesses among individuals exposed to petroleum hydrocarbons	Effect	Fair
Community risk perception							
Baptiste and Nordenstam	2009	Trinidad and Tobago	Cross-sectional	177 residents from 3 villages between, June to August 2006	Residents living closer to the drilling site had greater health and environmental concerns	Effect	Fair
Okoli	2006	Nigeria	Cross-sectional	42 rural participants	Rural communities affected by environmental degradation, pollution, job displacement and health concerns	Effect	Inadequate

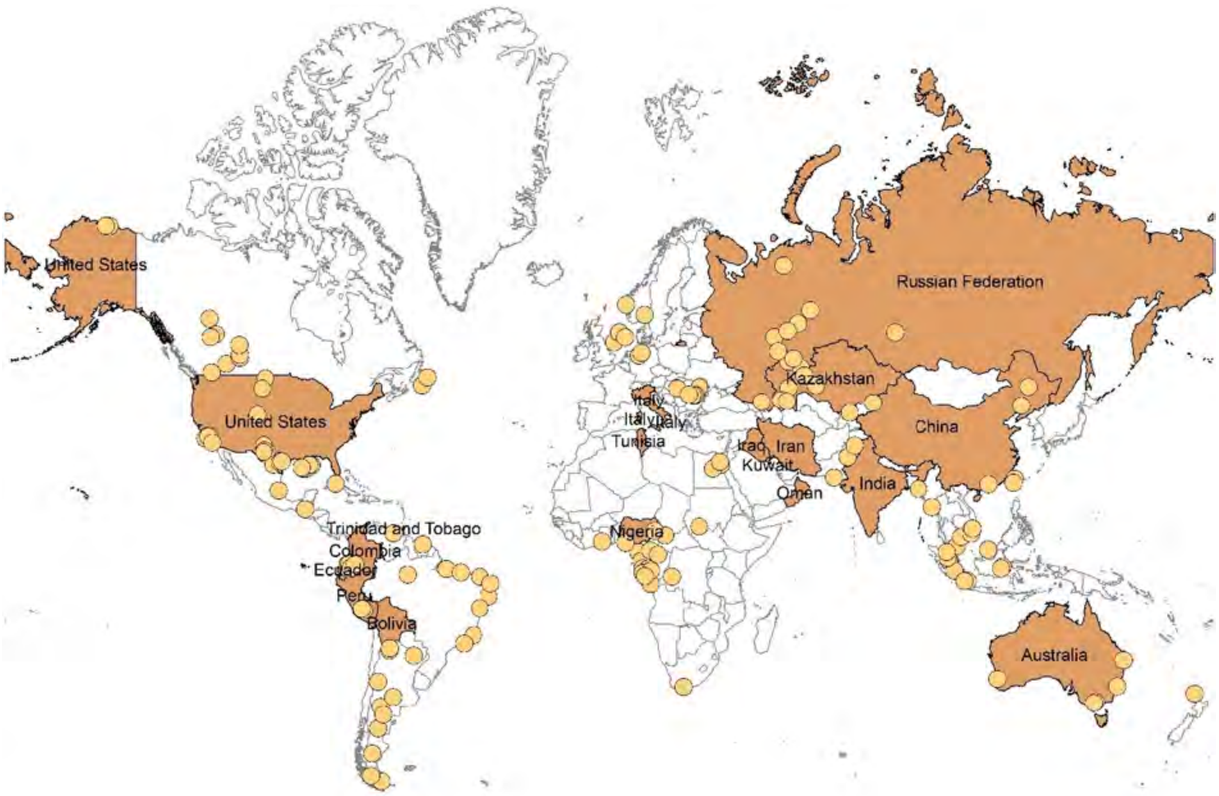

Fig. 2. Geographical distribution of known oil fields, designated by yellow dots. Shaded countries designate location of studies reviewed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.2. Worker health

A total of five studies explored health outcomes for occupational exposures associated with working in the onshore oil drilling industry. Two studies explored cancer risk, while the other studies examined upper respiratory tract bleeding, silica related illnesses, and neurobehavioral impairment.

The Australian Health Watch cohort, consisting of workers in the petroleum industry (including both extraction and refining), was designed to track both cancer incidence and deaths that may be associated with occupational exposure to oil-related chemicals using a national cancer registry. Among the cohort there was an observed low standard mortality ratio (SMR 0.84), suggesting a presence of the "healthy worker effect," lower cancer mortality and prolonged survival among this cohort (Gun, 2004). The results for cancer from a 15-year follow up showed a non-significant increase in the incidence of all cancers (SIR 1.04, 95% CI 0.97–1.11). Melanoma occurred in significantly increased rates (SIR 1.54, 95% CI 1.30–1.81), while other types of cancers—bladder, prostate, and blood—were only found to be marginally significant. Among the results reported for only onshore oil extraction job types, there was no significant elevated incidence of cancer.

Paz-y-Mino et al. (2008) in Ecuador found that blood samples of oil workers showed increased DNA damage and cancer risk compared to urban control populations. Participants exposed to hydrocarbons were also more likely to report acute symptoms such as fatigue, headache, nausea, and diarrhea (Paz-y-Mino et al., 2008). The work suggests that populations exposed to hydrocarbons are more susceptible to developing DNA damage. However, the study lacked a detailed assessment of the degree of exposure among the study participants.

An observational study administered heath questionnaires to employees presenting at an oil field clinic with symptoms associated with low-level exposure to hydrogen sulfide (H_2S) gas. Independent monitoring found H_2S gas levels to range between 4 and 50 ppm, with common symptoms reported by oil workers including bleeding of the nose, pharynx, gum, mouth, and tongue, during periods of elevated H_2S concentrations at drill sites (Mousa, 2015). Questionnaires were also utilized to exclude symptoms not associated with H_2S gas exposure (e.g. related to the flu or rhinitis); however, the exact degree of exposure per patient was not assessed, nor was the exact placement of the monitors detailed. Prolonged neurobehavioral impairment was also identified among workers experiencing the highest levels of H_2S (up to 50 ppm) (Mousa, 2015). Further, a case report described that a 24-year-old oil tester with acute exposure to an estimated level of 14,000 ppm of H_2S exhibited declines in "cognitive function, memory, visual perceptual and coordination, intelligence, and neurophysiologic functions" 49 months after the initial exposure (Kilburn and Warshaw, 1995).

Respirable crystalline silica was an occupational hazard presented to some oil field workers, which can cause silicosis, lung cancer, autoimmune disorders, and kidney disease (Castranova, 2000). Crystalline silica, or "frac sand", is injected along with water and chemicals into hydraulically fractured wells to open cracks and fissures underground to allow increased flowback of oil. Millions of pounds of sand may be used for a single well, with one study finding that 5 out of 11 US sites utilize hydraulic fracturing methods with a mixture of sand and water, exposing some workers to respirable silica levels 10 times greater than those deemed as safe by the US Occupational Safety and Health Administration (Esswein et al., 2013). However, individual levels of exposures were not assessed.

3.2.3. Community risk perception and environmental health

Two papers assessed the attitudes and beliefs of rural communities toward oil drilling and extraction activities using interviews and questionnaires designed to contextualize local residents' experiences and concerns (Brown, 2003). Among rural coastal communities of

Trinidad, villagers living closest to oil extraction regions expressed the strongest belief that oil drilling harmed the nearby communities by causing health problems and damaging the wetland ecosystem (Baptiste and Nordenstam, 2009). In Nigeria, residents reported adverse impacts of oil exploration on socio-economic livelihood and health. Residents believed that oil drilling was associated with decreased farmland productivity, decreased fish populations due to oil spills, adverse impacts on drinking water quality, and decreased animals for hunting due to noise (Okoli, 2006).

3.3. Animal biomonitoring

The health and exposure of animals, including wildlife, pets, or livestock, can serve as sentinels to understand the potential cumulative impacts of exposure to human health. Biomonitoring of animals can also provide information about specific toxicants in exposed areas. Typically, animals are continually exposed to ambient air, soil, and surface water, have shorter life-spans, and have more frequent reproductive cycles when compared to humans. Five studies investigated the exposure and biologic effects of living near an oil drilling operation among either livestock or native species (Table 2).

Bamberger and Oswald (2015) longitudinally investigated 21 cases related to animal health based on qualitative interviews. The animals lived within two miles of an intensively drilled region across five US states, with some animals directly exposed to drilling fluids and wastewater. In both companion and livestock animals, the most commonly reported health impacts were found in reproductive, neurologic, gastrointestinal, and respiratory systems, along with decreased growth and milk production. Reported symptoms were largely unchanged over the course of the study.

Two studies assessed heavy metals in organs of animals raised in oil producing regions and slaughtered for meat consumption. Researchers found that among sheep (but not cattle), proximity to oil wells was related to higher concentrations of Pb (liver) and Cd (kidney) and that levels of metals varied by geographic location of the livestock in southern Italy (Miedico et al., 2016). Among cattle in oil-producing regions in Colombia, Pb, Cd, and molybdenum were measured in the organs of slaughtered animals (Brown, 2003). In both studies, many of the individual samples exceeded permissible Pb and Cd levels as established by the European Commission. In addition to potential pathways of exposure to humans, exposure to Pb and Cd adversely affect livestock animals' reproductive and immune systems, harming offspring and increasing susceptibility to infections (Cai et al., 2009).

Sand lizards in Kuwait were used as a bio-indicator to study the health hazards of pollution related to oil wells in the desert. Reptiles are exposed to pollutants primarily through ingestion, dermal contact, and inhalation. Lizards and ants from the oil-extraction region were found to have significantly higher concentrations of polycyclic aromatic hydrocarbons (PAHs) measured in tissue from the whole body compared to tissues of animals from a control region. Specifically, phenanthrene, fluoranthene, and benzo[*a*]anthracene were found in both species found in the oil field region but not found in other sites (Al-Hashem, 2011). They also identified higher numbers of dead and swollen cells with cytoplasmic degeneration in the analysis of liver tissue from lizards in this region (Al-Hashem et al., 2007). In addition, damage was greater in male than in female lizards, suggesting an overall impact to an organism's growth, survival, and reproduction with exposure.

3.4. Environmental exposures and oil extraction

The literature on environmental contamination (Table 3) associated with oil drilling that may impact human health is typically focused on a specific medium—air, soil, or water (Fig. 3).

3.4.1. Air pollution

A single drill site typically operates for decades, and the extraction process itself produces emissions of multiple health-hazardous air pollutants, including chemicals such as benzene, toluene, ethylbenzene, xylene, formaldehyde, hydrogen sulfide, and methylene chloride (Field et al., 2014). Chemicals released into the air include particulate matter (PM), nitric oxides (NOx), methanol, naphthalene, xylene, toluene, ethylbenzene, formaldehyde, and sulfuric acid. Many of these compounds are known to be either toxic, carcinogenic, or associated with reproductive harm (Stringfellow et al., 2017). However, transport from the extraction site to human populations is less well-characterized, as understanding of the impact on local air quality is typically limited by the availability of existing monitoring networks. The emissions also likely depend on geographical location and state of drilling.

Table 2
Summary of animal biomonitoring, toxicological studies on health outcomes from exposures associated with oil drilling.

Author(s)	Year	Country	Study population	Findings	Health effect	Quality
Animal biomonitoring studies						
Al-Hashem et al.	2007	Kuwait	*A. scutellatus* lizards	Higher numbers of cells with cytoplasmic degeneration and dead cells among lizards living in oil-extraction region	Effect	Inadequate
Al-Hashem and Mona	2011	Kuwait	*A. scutellatus* lizards	Greater hepatotoxicity among adults (particularly males) exposed to oil pollution	Effect	Inadequate
Bamberger and Oswald	2015	United States	Companion and food animals	No significant changes to health of animals living within 2 miles of oil/gas well after 15–34 months	No effect	Fair
Bustamante et al.	2015	Colombia	Cattle	Excess lead and cadmium levels in liver, kidney and muscle of cattle near oil extraction sites represents a human health risk	Effect	Fair
Miedico et al.	2016	Italy	Cows and sheep	Bovine and ovine liver samples collected near oil wells showed accumulation of 18 heavy metals	Effect	Fair
Toxicological studies						
Odeigah et al.	1997	Nigeria	Onion (*A. cepa*)	Increasing concentrations of oil field waste water led to decreased root length and mitotic index, and increased morphological deformations	Effect	Fair
Wernersson	2004	Ecuador	Aquatic ecotoxicity	Acute water toxicity at all sites was not significantly high	No effect	Fair
Akani and Obire	2014	Nigeria	African catfish (*C. gariepinus*)	Exposure to sub-lethal concentrations of oil field wastewater led to increased bacterial concentrations in skin, intestine, and gill tissues	Effect	Fair
Kassotis et al.	2015	United States	Male C57BL/6J mice	Prenatal exposure to hydraulic fracturing chemicals caused decreased reproductive health and increased body weight, heart size, thymus size, and serum testosterone	Effect	Good
Abdullah et al.	2016	United States	Drilling fluids	Identified 28 different chemicals used for acidization known to be toxins	Effect	Good
Kassotis et al.	2016	United States	Female C57BI/6 mice	Prenatal exposure to hydraulic fracturing chemicals caused increased pituitary hormone levels and body weight and decreased reproductive health	Effect	Good

Table 3
Summary of literature on environment exposures associated with oil drilling.

Author(s)	Year	Country	Exposure	Findings	Quality
Abdul-Wahab et al.	2012	Oman	Air	Short-term levels of hydrogen sulfide gas from flaring exceeded acceptable standard	Fair
Macey et al.	2014	United States	Air	VOCs present near oil/gas drilling sites at levels above federal guidelines, concern to resident and worker health	Good
Novikova et al.	2014	Tatarstan Republic	Air	Significant correlation between pollutants in ambient air and number of diseases found in exposed population, suggesting delayed and cumulative effects of exposure	Poor
Spitz et al.	1997	United States	Drilling waste	Significantly higher levels of radium and other hazardous waste in former sludge pond and waste pit areas	Fair
Shadizadeh and Zoveidavianpoor	2010	Iran	Drilling waste	Heavy metal concentrations of reserve mud pit samples exceeded ACGIH standards	Fair
Hrichi et al.	2013	Tunisia	Drilling waste	Mean radium levels of oil fields above maximum safe standards	Fair
Rajaretnam and Spitz	2000	United States	Soil	About 1.3% of radium-226 in contaminated soil was found to leach into the environment	Good
Bojes and Pope	2007	United States	Soil	12–46% of total PAHs in soil near oil sites comprised of possible carcinogens, exceeding regulatory standards	Good
Jibiri and Amakom	2010	Nigeria	Soil	All radiation detected in crude oil sedimentation tank found to be derived from naturally occurring radionuclides	Fair
Kuang et al.	2011	China	Soil	Higher concentrations of PAH found with decreasing distance from the source of the oily sludge	Fair
Agbalagba et al.	2012	Nigeria	Soil	Radioactivity of oil field samples within allowable limits	Fair
Teng et al.	2013	China	Soil	Significantly higher concentrations of TPH in the oil field due to spills or leaks	Good
Fu et al.	2014	China	Soil	Cadmium is the most common, easily changing/mobile, and potentially harmful heavy metal found in oil-polluted soils	Good
Jie et al.	2015	China	Soil	Naphthenic acid levels of oil fields exceeded ecotoxic levels	Fair
Wang et al.	2015	China	Soil	Varying concentrations of carcinogenic PAHs in soil from oil fields, low cancer risk	Fair
Ajayi and Dike	2016	Nigeria	Soil	Higher risk for radiation exposure near active crude oil exploration, but levels are within permissible limits	Fair
Alawi and Azeez	2016	Iraq	Soil	Cancer risk for all sites within acceptable levels specified by US EPA	Fair
Olobaniyi and Omo-Irabor	2016	Nigeria	Soil	Neutral pH, low TOC, highly variable TPH, and slightly elevated levels of nickel in soil	Poor
Zhang et al.	2013	China	Soil	Level of PAH concentrations higher near the oil wells, presents risk of cancer	Fair
Asia et al.	2007	Nigeria	Soil and water	High levels of heavy metals detected in soil and water samples, some above natural levels	Fair
An et al.	2005	United States	Water	Groundwater under oil production sites higher in chloride, sodium, salinity, and conductivity	Fair
Moskovchenko et al.	2009	Russia	Water	Elevated concentrations of chloride, salinity, and total petroleum hydrocarbons	Fair
Alonso et al.	2010	Bolivia	Water	Contamination concentrations exceeded regulations in 76.19% of samples; contaminants included TPH, PAH, As, Mn and Fe	Fair
Ma et al.	2011	China	Water	Surface and groundwater quality severely impacted by pollution from petroleum drilling	Fair
Teng et al.	2013	China	Water	Higher TPH levels in aquifer near oil field from oil exploitation, transportation, and temporary storage	Good
Li and Carlson	2014	United States	Water	Methane in drinking water but not strongly associated with proximity to extraction sites	Good
Moquet et al.	2014	Peru	Water	Oil extraction activity significantly impacts concentrations of dissolved Na and Cl of the Amazon basin	Fair
Lauer et al.	2016	United States	Water	Occurrence of spills is strongly associated with oil well density, spill water violates regulations contaminant levels	Good
Li et al.	2016	United States	Water	No aqueous phase contamination of groundwater detected	Fair
Cozzarelli et al.	2017	United States	Water	Persistent pollution from oil/gas wastewater spill despite remediation efforts	Good

3.4.1.1. Organics. Macey et al. (2014) leveraged community knowledge to identify and install air sampling equipment in particularly noxious locations near oil drilling sites across five states. Of the 75 volatile organic compounds analyzed, 8 were identified at concentrations exceeding the US Environmental Protection Agency chronic cancer-risk threshold (assuming >365 days of exposure): benzene, 1,3 butadiene, ethylbenzene, formaldehyde, n-hexane, hydrogen sulfide, toluene, and xylenes (Macey et al., 2014). Benzene, formaldehyde, and hydrogen sulfide were the most frequently detected at excess levels.

Pathway	Inorganics	Organics	Radioactive
Air	SO_2	Benzene, Formaldehyde, H_2S, VOCs	
Water	As, Cl^-, Mn, Na	CH_4, PAHs, TPH	
Drilling waste	As, Ba, Cd, Cl^-, Cr, Mn, Na, Ni, Pb, Se, V	PAHs	NORM, Radium
Soil	Cd, Cr, Cu, Pb, Zn	Naphthenic acids, PAHs, TPH	NORM

Fig. 3. Summary of potential exposure pathways and contaminants measured.

An analysis of the air quality in an oil-extraction region of Tatarstan Republic, Russia measured hydrogen sulfide, hydrocarbons, benzene, sulfur dioxide, and nitrogen oxide gas (Novikova et al., 2014). Benzene and hydrogen sulfide were the largest contributors to the total estimated non-carcinogenic risk for nearby populations, with the highest risk estimated for children. Elevated risk was further calculated for the respiratory and cardiovascular systems. However, the study lacked detailed information on both the procedural and analytic methods utilized for the conclusion.

Another set of researchers measured concentrations of sulfur dioxide (SO_2) in the desert oil fields of Oman attributed to the local flaring of gas (Abdul-Wahab et al., 2012). Flaring is a widely used practice for the disposal of natural gas during drilling and production in places where there is insufficient infrastructure for the utilization of the gas. At sites most impacted by flare emissions, the average monthly concentration of SO_2 gas was 80 μg/m^3 with peaks exceeding 1300 μg/m^3. The one-hour US National Ambient Air Quality Standard is 196 μg/m^3.

Inhalation of low concentrations of SO_2 for short-term exposures (≤1 h) has been known to cause bronchoconstriction, shortness of breath, and wheezing (Reno et al., 2015). Oil field workers in particular could experience adverse, acute health effects even with short-term exposures to sulfur dioxide emissions (Abdul-Wahab et al., 2012).

3.4.2. Soil

Contamination of the earth occurs when drilling fluids are spilled during transport by truck or wastewater pipelines, failure of well casings, or leaks from tank pipes (Pichtel, 2016). Polluted lands can then impact human health through direct ingestion, crops, dermal contact, indoor and outdoor inhalation of soil particulates, and/or migration to groundwater, with field workers and nearby communities at highest risk for exposure.

3.4.2.1. Organics. Hydrocarbons, primarily measured as total petroleum hydrocarbons (TPH), comprise the major component of crude oil profiles, with hundreds of individual chemicals in a single TPH mixture. These profiles may vary between oil fields. A comparison of TPH soil concentrations between oil fields and farmlands in China found significantly higher concentrations in the oil fields, particularly in the top 15 cm of soil, likely as a result of direct oil spills or leaks (Teng et al., 2013). Similar results were observed around oil production sites in Nigeria, where the TPH concentrations are expected to have adverse effects on soil quality and microorganism health (Olobaniyi and Omo-Irabor, 2016). Naphthenic acids, for example, are a naturally occurring component of nearly all crude oils and can persist in water and accumulate in sediments. These compounds have been found to be toxic to microorganisms, aquatic organisms, birds, and mammals (Brown and Ulrich, 2015). An investigation across four oil fields measured naphthenic acids in all samples, and many samples were found to be at concentrations that exceeded reported ecotoxicity thresholds (Jie et al., 2015).

Polycyclic aromatic hydrocarbons (PAHs), a group of environmentally toxic and persistent chemicals associated with crude oil, enter the environment through spillage or leaks from producing wells, storage tanks, transportation lines, and/or waste pits. In Texas, soil analysis of oil extraction sites found that 12–46% of the total PAH contaminants were comprised of known carcinogens (Bojes and Pope, 2007). Furthermore, concentrations of these PAHs exceeded Texas residential soil standards by up to 59 times the limit and groundwater protective levels by 4 times the screening criteria. Another study characterizing the concentrations of PAHs in soil across an agricultural and industrial region in China found higher levels in oil extraction fields compared to other sites, suggesting the direct contamination of local soil by the surrounding oil drilling activities (Zhang et al., 2013), which based on a risk assessment model, may increase risk of cancer in the local population. A separate analysis of surface soil samples from four oil fields across China identified heavily contaminated soils with a petroleum related PAH-signature (Wang et al., 2015). The possibly carcinogenic PAHs accounted for 8–27% of total PAHs, with the authors finding a similar cancer risk to Zhang et al. (2013). In addition, a similar study of PAHs in Iraqi oil fields modeled a comparable, but slightly lower, potential cancer risk for exposures (Alawi and Azeez, 2016).

3.4.2.2. Inorganics. Concentrations of heavy metals in oil have also been assessed with respect to oil extraction. Crude oil contains metals such as Cd, Pb, nickel (Ni), and vanadium (V), and drilling fluids may additionally contain chromium (Cr) and zinc (Zn), although composition can vary by oil field (Lord, 1991). In a soil content analysis for a Chinese oil field, the heavy metals Zn, Cd, and copper (Cu) were found to be significantly higher than background concentrations, with the highest concentrations being found near the oldest oil wells that were developed >40 years prior (Fu et al., 2014). The researchers concluded that Cd is the most bioavailable heavy metal in oil-polluted soils and the most threatening to the surrounding ecosystem. Similarly, an investigation in Nigeria identified elevated concentrations of Pb, Cd, Cr, and Zn when compared to background levels in soils (Asia et al., 2007).

3.4.2.3. Radioactive materials. Others have investigated the relationship between oil extraction and the presence of naturally occurring radioactive materials (NORM, e.g. ^{226}Ra, ^{232}Th and ^{40}K) in surface soils. Exposure to such radioactive materials can cause cell damage, anemia, birth defects, and respiratory harm and is associated with the increased incidence of cancer (Rich and Crosby, 2013). A comparison of soils in a region with untapped crude oil deposits to oilfields with active oil exploration measured 2–10 times higher concentrations of natural radionuclides in the active exploration regions, suggesting that active oil exploration leads to increased radionuclide concentrations in surface soils (Ajayi and Dike, 2016). While the population living near active oil exploration sites was estimated to have higher risk exposure to radiation hazards, that risk analysis did not exceed the maximum permissible limit established by the International Commission on Radiological Protection (ICRP, 1999). Furthermore, another study in Nigeria also measured elevated radioactivity levels in the soil of 10 oil fields compared to background levels (Agbalagba et al., 2012). The authors in this study also concluded that the radioactivity levels did not pose an immediate health risk but suggested a potential for long-term effects for oil field workers and nearby residents.

3.4.3. Water

The quality of surface water is influenced by local land use and both point and non-point sources that discharge into the water basin. Several studies have evaluated the role of oil extraction on local surface and groundwater quality; particularly, research has focused on changes in the chemical composition of the water.

3.4.3.1. Surface water. A river basin in Western Siberia, home to over 112 oil fields and >70,000 drilled wells, measured elevated levels of chloride and higher salinity in the surface water, suggesting release of oil-related wastewater through leakage, dumping, or seepage from contaminated groundwater (Moskovchenko et al., 2009). A similar study in a small river basin in the Peruvian Amazon impacted by oil extraction also found that oil activity was responsible for 20% of the chloride and 12% of the sodium content in surface waters (Moquet et al., 2014). The authors concluded that oil extraction activities could not be considered as negligible in terms of the impact on surface water hydrochemistry, with increased risk following the populations in this region who are in frequent contact with the contaminated surface water. In the US, an Oklahoma groundwater study found higher levels of chloride, sodium, and other salts in shallow groundwater sources beneath oil production areas compared to areas of residential or agricultural land use, which was attributed to oil drilling wastewater (An et al., 2005). In China as well, an oil field with over 3800 wells in the eastern Gansu Province found high salinity and TPH concentrations in the local ground and surface water, suggesting the significant degradation of water quality due to local oil drilling activities (Ma et al., 2011).

3.4.3.2. Drinking water. A group of studies assessed the presence of chemical contaminants in drinking water sources near oil fields. A study in southeastern Bolivia measured the levels of TPH, PAH, and 22 metals in the drinking water of residents living <30 km from an oil extraction field (Alonso et al., 2010). With surface waters acting as the primary source of drinking water for these rural communities, the study found high levels of exposure: three-quarters of the samples were contaminated with concentrations exceeding the reference levels. The most frequently detected contaminants were TPH, PAH, arsenic (As), and manganese (Mn). In the US, an investigation in Colorado examined the association between groundwater methane concentrations, which can indicate a seepage pathway of natural gas due to hydraulic fracturing, and proximity to oil and gas production. While methane was identified in drinking water, there was not a strong association with proximity to extraction sites (Li and Carlson, 2014). A further study looking at the transport pathways of contaminants into aquifers from leaking well casings near oil and gas production regions also found no evidence of aqueous phase contamination; however, the authors suggest that the results are inconclusive due to data and methods limitations (H. Li et al., 2016). In contrast, a groundwater TPH investigation in China found higher levels in a confined aquifer near an oil exploration field in comparison to that near a farmland, suggesting the direct contamination of the aquifer from exploratory wells, injection well leakages, and open well holes (Teng et al., 2013).

3.5. Drilling fluids, wastewater, and oilfield waste pits

The occurrence of spills is strongly associated with oil well density, indicating that areas with dense oil drilling are more likely to experience spills (Lauer et al., 2016).

3.5.1. Inorganics and organics

Based on state government records, North Dakota was estimated to have had >8000 spills from 2008 to 2015, involving over 53 million L of wastewater concentrated in the northwest oil fields (Cozzarelli et al., 2017). The wastewater was high in salts (chloride and sodium) and contained high concentrations of other toxic contaminants including barium (Ba), Cd, Ni, Mn Pb, selenium (Se) and V at amounts exceeding national ecological or drinking water regulations (Lauer et al., 2016). Accordingly, a detailed investigation of one major oil wastewater spill in North Dakota levels of chloride and sodium were 10–70 times greater than those found prior to the spill. Oil spills may introduce compounds into the ecosystem due to partitioning into the sediment layers, acting as long-term sources of contaminants for aquatic organisms (Cozzarelli et al., 2017).

Drilling fluids are injected into wells during the drilling process to aid in clearing, cooling the drill bit, and maintaining proper pressure during oil extraction. These oil- or water-based fluids can be discharged into oil field pits with the potential to leach directly into the soil or groundwater, which may in turn expose local populations. A study in Iran measured elevated concentrations of Cd, Cr, and Ni in the drilling fluids used in well sites, with significant concentration variations over an 8-month period (Shadizadeh and Zoveidavianpoor, 2010). Kuang et al. (2011) found that agricultural lands around the Zhongyuan oil field in China contained 435–4112 mg/kg total PAHs, with increasing concentrations with decreasing distance to the oil waste pits (Kuang et al., 2011).

3.5.2. Radioactive materials

Human exposures to such contaminations could occur through the inhalation of radium from the surface, through ingestion of animals that grazed on the site, or through food grown in the contaminated soil. Elevated concentrations of radioactive materials, in additional to the heavy metals As and Pb, in areas which formerly served as waste pits and sludge ponds were measured on farmland from a former oil drilling site in Eastern Kentucky (Spitz et al., 1997). A later investigation suggested that the leachability of radium and other radioactive contaminants on farmland is another important factor for estimating risks to human health as a result of legacy oil drilling activities (Rajaretnam and Spitz, 2000). In Tunisia, waste samples from onshore oil field production regions had the highest levels of radium isotopes, with estimated annual effective radiation doses exceeding the levels deemed allowable by the United Nations Scientific Committee on the Effects of Atomic Radiation (Hrichi et al., 2013). The same team also found that the radioactivity of the oil field directly increased along with the amount of wastewater being used in the processes. However, a Nigerian study measuring NORM levels in the soil waste stream did not pose a significant risk to workers or residents based on the calculated cancer mortality risk (Jibiri and Amakom, 2010).

3.5.3. Toxicological studies of oil drilling related fluids

Researchers have investigated the toxicological profile of both the fluids used for injection into petroleum wells for stimulating production and the wastewaters collected from such extraction wells (Table 2). In a review of data collected by regulatory agencies on acidization, or the use of fluids for enhancement of oil production, Abdullah and colleagues identified 600 instances of acidizing over the course of 16 months in California (2016). Twenty-eight of the chemicals used recently by oil operators are known to be carcinogens, mutagens, reproductive and developmental toxins, endocrine disruptors, or other acutely toxic chemicals like xylene, hydrofluoric acid, methanol, and nitriloacetic acid. Again, such compounds can enter the environment through spills, leaks, and volatilization, but in general are poorly characterized in terms of transport through and persistence in the environment (Stringfellow et al., 2017).

Agriculture and fishing are sectors that are vulnerable to environmental pollution related to oil extraction because they are closely intertwined with our ecosystems. The biological impact to these sectors can result in not only economic declines but also the more direct impact to our health and well-being. For example, Akani and Obire (2014) simulated the impact of disposing wastewater into local surface water sources on the native catfish population. The study exposed African catfish to sub-lethal doses of raw wastewater effluent. In general, as the dose of wastewater increased, the bacterial counts on the skin, gills, and intestines of the fish also increased. The authors suggest that the presence of potential pathogens in the wastewater, including *Bacillus*, *E. coli*, and *Staphylococcus* could contribute to bacterial diseases for fish living in waters impacted by wastewater from oil drilling operations, leading to economic loss and public health hazards (Akani and Obire, 2014).

The degree of contamination, toxicity, and phototoxicity caused by seepage from production pits and wastewater runoff in water sources was also assessed in the oil producing regions of the Ecuadorian Amazon (Wernersson, 2004). TPH could be identified in rivers and ponds used for drinking water; however, the acute water toxicity was determined to be low when analyzed through bioassays. Others have investigated the genotoxicity of wastewater on native onion varieties, finding a negative dose-response relationship between root growth and oil wastewater concentration through root damage and growth inhibition (Odeigah et al., 1997). Root malformations and statistically significant chromosomal aberrations were also observed, indicating possible genotoxicity for exposed plant life.

Kassotis and colleagues (Kassotis et al., 2015; Kassotis et al., 2016) examined the endocrine-disrupting properties of chemicals used or produced during the petroleum extraction process to reduce friction, decrease drilling time, or enhance the recovery of oil (Wiseman, 2009). Over 100 chemicals associated with oil or natural gas extraction are known or suspected to be endocrine disruptors. The studies investigated the potential range adverse reproductive and developmental health outcomes in mice after exposing them prenatally to a mixture of 23 chemicals prepared in the lab, in order to replicate the fluids used in unconventional oil and gas extractions. The results included decreased pituitary hormone levels, increased body weights, disrupted development of ovarian follicles, and altered uterine and ovary organ weights for female off-spring (Kassotis et al., 2016). Among their male counterparts, increased testes weights, serum testosterone, body weights, and cardiomyocyte size and decreased sperm counts were observed (Kassotis et al., 2015). For all exposed groups, adverse effects to fertility could be found, even for those exposed to the lowest doses, which suggests that any level of pollutants from extraction sites may prove to be hazardous—even those coming from wells near communities which are deemed to be low impact.

4. Discussion

Based on a review of existing scientific literature and peer-reviewed studies, current evidence suggests a potential wide range of risks associated with upstream oil drilling that occurs close to human and animal populations. Various pathways such as air, water, and soil have been found to transmit pollutants associated with oil drilling operations, and multiple studies suggested higher disease prevalence in communities near such operations. As oil extraction activities are expected to become more common near where people live, work and play, such exposure pathways may become an important public health consideration.

There are few epidemiological studies identified related to upstream oil extraction, with the majority located in the Amazon region of South America. The methods reviewed also typically made comparisons between an exposed and unexposed (or less exposed) group, which does not allow for a robust assessment of dose-response trends, specific exposure pathways, acute impacts, cumulative effects, or variation across oil extraction regions. There are multiple studies that suggest evidence of association with cancer, although the results are not always consistent and rely on secondary surveillance data. In most cases, studies were based on existing disease surveillance systems and did not directly measure exposure or disease status.

Across the studies reviewed, the health endpoints are generally non-specific, that is having multiple potential causes and only assessed at multiple time points. While community health studies can identify impacts on vulnerable populations (children, elderly, etc.), additional studies among workers could offer greater insights into the health implications of oil drilling since they are the first to be exposed and usually at the highest levels possible. Secondly, epidemiological studies routinely relied on residential proximity to gauge magnitude of exposure. Since intense drilling areas may have multiple drilling pads spaced closely together with potential for multiple exposure pathways (air, water, soil), distance is a reasonable proxy for potential cumulative exposure. Nevertheless, the use of different approaches to defining the exposure make it difficult to compare across studies, since both the extent of exposure (over both space and time) and what this potential exposure means to humans and animals living nearby is variable. The limited range of studies also creates a gap in understanding the episodic nature of potential exposures and how they may influence the indoor living environments of communities.

Among the studies considered in this review, there is a larger body of literature regarding exposure and environmental contamination associated with oil drilling when compared to epidemiological analyses. These studies typically assessed the behavior of one contaminant group in a single environmental medium. Despite varied methodological approaches and diverse oil field settings, a pattern of elevated heavy metal, hydrocarbon, and radioactive material (particularly in the soil) concentration emerged across the literature. However, the conclusions on the risk these elevated concentrations pose to human populations vary widely, depending on the exposure patterns specific to that community (e.g. drinking water source, local food, occupation, etc.).

4.1. Future research

There persist important limitations in the existing research and a need to extend the understanding regarding the public health dimensions of oil extraction processes. Therefore, larger studies, with greater statistical power and more spatially refined exposure assessments are needed to better characterize impacts on mortality, morbidity, and mental health endpoints. Furthermore, there is a need for baseline data (prior to oil drilling), prospective exposure monitoring, and health surveillance of populations living near oil developments in order to better assess causality (Finkel and Hays, 2015). While many health studies pointed to air pollution as a key driver for potential adverse health effects, few studies investigated the relationship between air quality and oil extraction. No studies reviewed to date have published longitudinal physiological measurements from a cohort near an oil extraction site, and few evaluate the potential impacts of unconventional extraction technologies or frequency of flaring.

Future research required to address the multiple gaps in understanding the upstream oil impacts will require the utilization of improved methodologies. For example, the use of multiple continuous monitors that use innovative, low-cost, and highly portable electrolytic sensors (Collier-Oxandale et al., 2018), capable of measuring in the parts-per-billion level range, can enable the use of temporal and spatial-scale data highly relevant to realistic patterns of human exposure to ambient air pollution (Clements et al., 2017). Technological advances allowing the capture of higher resolution data may better support epidemiological designs, even evaluating the dose-response relationship between exposure and health outcomes. Finally, there is a need for continued investigations into whether specific populations are more susceptible to or disproportionately impacted by oil drilling-related pollution than the general population (Johnston et al., 2016; McKenzie et al., 2016; O'Rourke and Connolly, 2003). Susceptibility factors may relate to life stage, genetic predispositions, co-morbidities, socioeconomic status, race and/or ethnicity.

As unconventional techniques expand oil production globally into previously inaccessible sources within existing communities, more humans and animals will be exposed to oil-related contaminants. Unconventional drilling techniques are not only dramatically changing the geography of oil production but are also changing our estimates of oil and gas reserves (Lave and Lutz, 2014). Global estimates for recoverable unconventional oil deposits order near 345 billion barrels, which suggest that oil drilling practices may not decrease anytime soon and may even become more harmful to public health (Jackson et al., 2014). In the US, hydraulic fracturing accounted for <2% of total oil production in 2000 but has rapidly grown and accounted for nearly half of all oil extracted in the US in 2015 (EIA, 2018).

Although we used a broad search strategy and consider this a substantive review of the available literature, there are limitations to this study. Some relevant publications or data could have been neglected in our search due to the search terms used for each database although efforts were made to be as inclusive as possible. Furthermore, there are many countries with high volumes of oil extraction and potentially high exposure levels such as Saudi Arabia, Mexico, or the United Arab Emirates, for which no studies were identified that met the criteria (e.g. peer reviewed paper in English or Spanish).

5. Conclusion

In this review, we focused on the peer-reviewed scientific literature addressing the various dimensions of upstream oil extraction activities on environmental health. There is growing evidence of health impacts in communities near oil extraction compared to other populations and potential for multiple pathways of exposure to oil-related chemicals. Although various impacts associated with exposure to oil drilling activities were identified, studies ranged in methodology and assessment of both exposures and effects. In order to more clearly assess the range of impact that oil drilling operations may have on public health, future studies will need to improve on defining related exposures, using better equipment and more consistent methodology.

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Exhibit 38.07

This exhibit was not previously submitted in November 2023

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Changes in neighborhood air quality after idling of an urban oil production site†

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Oil and gas development is occurring in urban, densely populated neighborhoods; however, the impacts of these operations on neighborhood air quality are not well characterized. In this research, we leveraged ambient air monitoring adjacent to an oil and gas production site in Los Angeles, California during active and idle periods. This study analyzed continuous methane (CH_4) and non-methane hydrocarbon (NMHC) measurements, together with triggered grab samples and 24 hour integrated canister samples collected by the South Coast Air Quality Management District. Ambient air pollutant levels and trends were evaluated during active and idle well operations to assess changes in neighborhood air quality after the suspension of oil and gas production. We find that mean concentrations of methane, NMHC, benzene, toluene, ethylbenzene, xylenes, styrene, *n*-hexane, *n*-pentane, ethane, and propane decreased following the stop in production activities. Using a source apportionment approach, we observed that the "natural gas" drilling source contributed 23.7% to the total VOCs measured during the active phase, and only 0.6% to the total measured VOCs in the idle phase. Near urban oil and gas production sites, residents may face poorer air quality due to the oil and gas activities which may pose adverse health and environmental risks among proximate communities.

Environmental significance

Modern oil development frequently occurs in close proximity to human populations. Los Angeles, California is among the largest urban oil field in the country and home to thousands of active oil wells in very close proximity to homes, schools and parks, yet little is known about impacts on air quality. In this study, we leverage fenceline ambient air monitoring during active production and after the site went idle to assess concentrations of methane and non-methane hydrocarbons. Concentrations of air pollutants associated with oil drilling decreased following the stop in production activities. Residents may face poorer air quality due to the proximity of oil and gas activities, even in urban environments.

Introduction

Modern oil development frequently occurs in close proximity to human populations. In the United States (US), oil production has nearly doubled to 9.4 million barrels per day between 2008 and 2015, reversing a longstanding decline in production.[1] An estimated 17.6 million people live within 1.6 km of a confirmed active oil or gas well in the continental United States.[2] Living near oil and gas infrastructure has been associated with various acute health symptoms, including respiratory distress; nose, eye, and throat irritation; headaches; and fatigue, among others.[3–7] Increased hospitalization rates,[8] higher risk of pre-term birth[9,10] and higher asthma incidence[11] have also been observed.

Oil and natural gas extraction activity, using both traditional primary production methods as well as secondary methods such as flooding, steam injection, hydraulic fracturing, and acidization has prompted concerns over air quality impacts across the United States. A single drill site typically operates for decades, and the extraction process itself produces emissions of multiple air pollutants, including methane and volatile organic compounds (VOCs), among others.[12–16] These compounds can enter the nearby environment through spills, leaks, volatilization and disposal of wastewater, but in general, are poorly characterized in terms of their transport through and persistence in the local environment.[17–22] There is limited information on impacts to local air quality and emissions of air pollutants associated with the upstream oil development process to nearby neighbors, particularly in urban areas.[23]

Los Angeles (LA) County, California, is home to one of the most petroleum-dense basins in the world, with thousands of extraction wells spread across multiple oil fields.[24,25] Land

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development, population growth and oil exploration in Los Angeles occurred concurrently, leaving a patchwork of thousands of active oil wells operating in very close proximity to homes, schools and parks.[26] Approximately 500 000 residents live within <$\frac{1}{4}$ mile (∼400 m) of an active oil developing site.[26] However, limited studies in LA coupled with poor historical data collection results in limited understanding of the role of urban oil drilling on neighborhood air quality.[27]

AllenCo Energy operates a drill site with a total of 21 wells drawing from the Las Cienegas oilfield, southwest of downtown LA. The AllenCo facility opened in the 1960s and includes an on-site crude oil, water, gas separation system and natural gas treating equipment. The site sits less than 30 m from a multi-unit residential housing development and adjacent to a high school and a university campus. After an upswing in oil production at the facility in 2010, nearby residents began to report noxious odors and adverse acute health symptoms, such as dizziness, nosebleeds and headaches, ailments that have been observed in other areas with oil and gas production.[28,29] The site quadrupled production from 2010–2013 compared to 2009 levels, growing from 4484 barrels of oil to nearly 27 000 barrels of oil by 2010. The South Coast Air Quality Management District (SCAQMD) received nearly 300 complaints from residents living within the vicinity, conducted over 150 inspections and reported 18 violations.[30] In response, SCAQMD implemented air quality monitoring to measure the oil and gas related air contaminants near the facility in October 2013. Soon after federal officials visiting the operations became sickened on-site and complained of strong odors, sore throats, coughing, and severe headaches, AllenCo suspended production.[31,32] We leverage this change in activity to evaluate changes in neighborhood air quality.

Materials and methods

We analyzed air monitoring data collected during an active oil and gas production phase and after operations voluntarily ceased by the local regulatory agency, SCAQMD, to assess changes in neighborhood air quality from October 2013 to December 2016 near the AllenCo drill site in Los Angeles, CA. Real-time methane and non-methane hydrocarbons were measured in parts per million (ppm) from October 4, 2013 to March 18, 2014 nearly every ∼10 seconds using a MOCON gas-chromatograph analyzer. The trailer was situated at the eastern edge of the fenceline of the facility (Fig. 1). Approximately 30% of samples were taken prior to the voluntary shutdown of oil and gas production.

For analytical purposes, we divided the time frame into three phases to assess changes before, during and after oil production ceased. Phase 1 covered active operations (October 4, 2013–November 21, 2013); Phase 2 covered the period immediately after voluntary closure as maintenance, odor complaints and repair activities occurred in the absence of oil or gas production[33] (November 22, 2013–January 31, 2014); and Phase 3 covered the idle period (February 1, 2014–March 18, 2014). The real-time data is summarized as hourly averages for analytical purposes. Instrument maintenance and calibration breaks were recorded 41 times during the monitoring period, ranging from minutes to days and are excluded from the analyses. Negative concentrations of NMHCs appeared only after February 18, 2014 and were also removed, accounting for ∼2% of the total recorded observations. These values were reassigned to zero to calculate minutely (or hourly) averages.

Canisters were collected at the adjacent Mount St. Mary's College (Fig. 1) beginning in October 2013 while the facility was active and analyzed for hydrocarbons using gas chromatography and flame ionizations detection (FID) PAMS analytical methods by the SCAQMD. A total of 115 24 hour canister samples were collected approximately every four to six days between October 2013–January 2014 and approximately every 6–10 days between February 2014–December 2016. Forty-four additional canister sampling events were "trigger" samples, *i.e.*, collected when continuous CH_4 monitors measured elevated concentrations. The site was located at an apartment complex across the street from the facility. These samples were collected for 5 minutes. All samples were analyzed by an in-house SCAQMD laboratory in Diamond Bar, CA, and PDF copies of the lab reports were made available through the SCAQMD. Data were downloaded and digitized in preparation for analysis. We compared samples collected during active operations (October 4, 2013–November 21, 2013) to those collected during the idle period (February 1, 2014–December 31, 2016). Of the 56 hydrocarbons measured, we focused on 17 compounds: ethane, ethylene, acetylene, propane, *n*-butane, *n*-pentane, isoprene, *n*-hexane, *n*-heptane, benzene, toluene, ethylbenzene, *m*-*p*-xylene, *o*-xylene, styrene, *n*-octane and *n*-decane based on existing literature of air quality near oil and gas, traffic-related pollutants and detection frequency.[23,34] All datasets were analyzed in STATA IC 14 and MatLab, including the gramm toolbox.

Comparisons across the state and to health-based references

Concentrations of CH_4 and NMHC measured at the fenceline of AllenCo were compared to measurements available during the same time period from monitors operated by the California Air Resources Board across the state of California. Canister samplers were compared to the California Office of Environmental Health Hazard Assessment's (OEHHA) Reference Exposure Levels (REL).[19,35] RELs are shown in parts per billion by volume (ppb) using assumptions of standard temperature (25 °C) and pressure (101.325 kPa). Chronic RELs were presented in the absence of acute values.

Source attribution approach for passive samples

The AllenCo oil and gas development sites operate in a neighborhood situated near two freeways. To evaluate potential emission sources, we first investigated pollutant concentrations using various bivariate plots. Acetylene is commonly found in vehicle emissions,[36] while short-chain alkanes, like *n*-butane, *n*-pentane and isopentane, are observed in enhanced concentrates near natural gas.[37–39] We utilized source apportionment analysis using the Positive Matrix Factorization (PMF) model v5.0 to resolve and quantify the contributions of the major

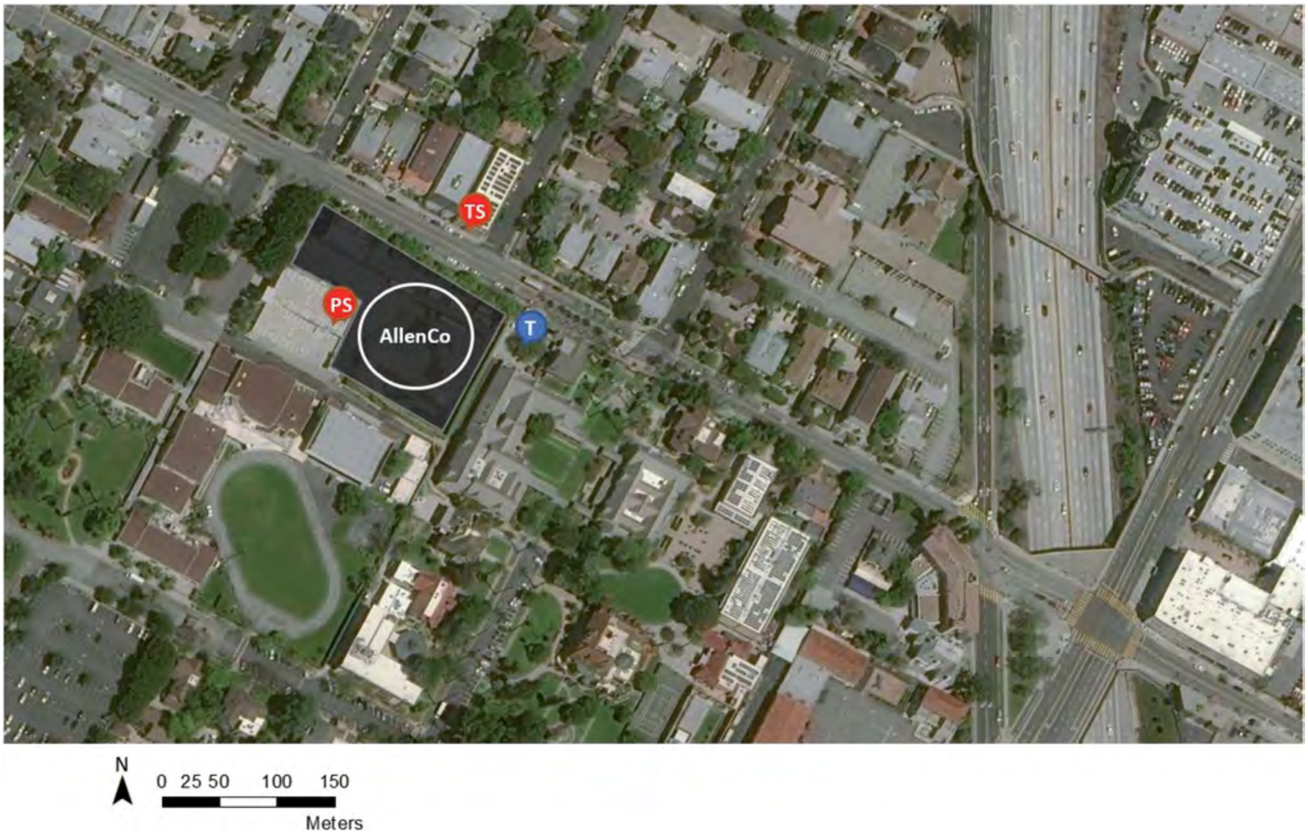

Fig. 1 Satellite image of the AllenCo facility (shown in black) with location of the continuous monitoring trailer (blue T), passive canister sampling location (PS) and trigger sampling location (TS). Imagery adapted from ESRI.

sources or source "groups" contributing to the observed VOCs concentrations across the 115 24 hour passive canister samples. PMF is a multivariate factor analytical model originally developed by Paatero[40] and further refined by the US Environmental Protection Agency.[41] PMF implements the following equation:

$$X_{ij} = \sum_{k=1}^{p} g_{ik} f_{kj} + e_{ij} \tag{1}$$

where X_{ij} is input data matrix (*i.e.*, ambient measurements) with i number of samples and j number of chemical compounds or species, p is the total number of factors (*i.e.*, sources) contributing to the input data matrix (assigned by the user), g is the contribution of each factor, f is the chemical profile (*i.e.*, source signature) of each factor, and e_{ij} is the residual error. The uncertainty (U_{ij}) was calculated for each species concentration using the available method of detection limit (MDL_j). If a species concentration was above the MDL_j, the uncertainty was calculated using the following equation:

$$U_{ij} = \sqrt{\left(0.5 \times \mathrm{MDL}_{ij}\right)^2 + \left(\text{error fraction} \times X_{ij}\right)^2} \tag{2}$$

Species concentrations below the MDL_j were replaced by $\frac{1}{2}\mathrm{MDL}_j$, and their uncertainties set to $5/6\mathrm{MDL}_j$.[42] We examined different number of factors (4–8) (ESI, Table S2†), but 6 factors were the maximum number of factors corresponding to meaningful sources.

Results and discussion

Ambient air quality hydrocarbon data

The real-time ambient monitoring period covered 3243 hours of methane and NMHC measurements (Fig. 2). The average concentration of methane was 2.10 ppm (sd: 0.87 ppm). Prior research in California shows the typical background CH_4 concentrations range from 1.7 to 2.0 ppm.[43,44] Concentrations above the background levels may suggest a local source. When assessing by phase, the mean concentration of methane declined from 2.53 ppm (1.03) to 2.15 ppm (0.77), and 1.68 ppm (0.35), for phases 1, 2 and 3 respectively (Table 1). The CH_4 levels observed in phase 3 are consistent with prior studies finding average concentrations in Los Angeles basin ranging from 1.75–2.2 ppm.[44,45] The average NMHC concentrations also decreased after production ceased (Table 1). During operations, the maximum one-minute averaged real-time concentrations reached 37.54 ppm for methane and 157.0 ppm for NMHC. By phase 3, the highest measured concentrations observed were 6.09 ppm for methane and 31.76 ppm for NMHC. The fenceline concentrations of both methane and NMHC during phase 1 were statistically higher than in phase 2 or 3 ($p < 0.01$) based on the Wilcoxon–Mann–Whitney test. The wind direction was similar during the three phases (ESI Fig. S1†).

We investigated the hourly trends to determine how pollutants concentrations vary throughout the day during the three

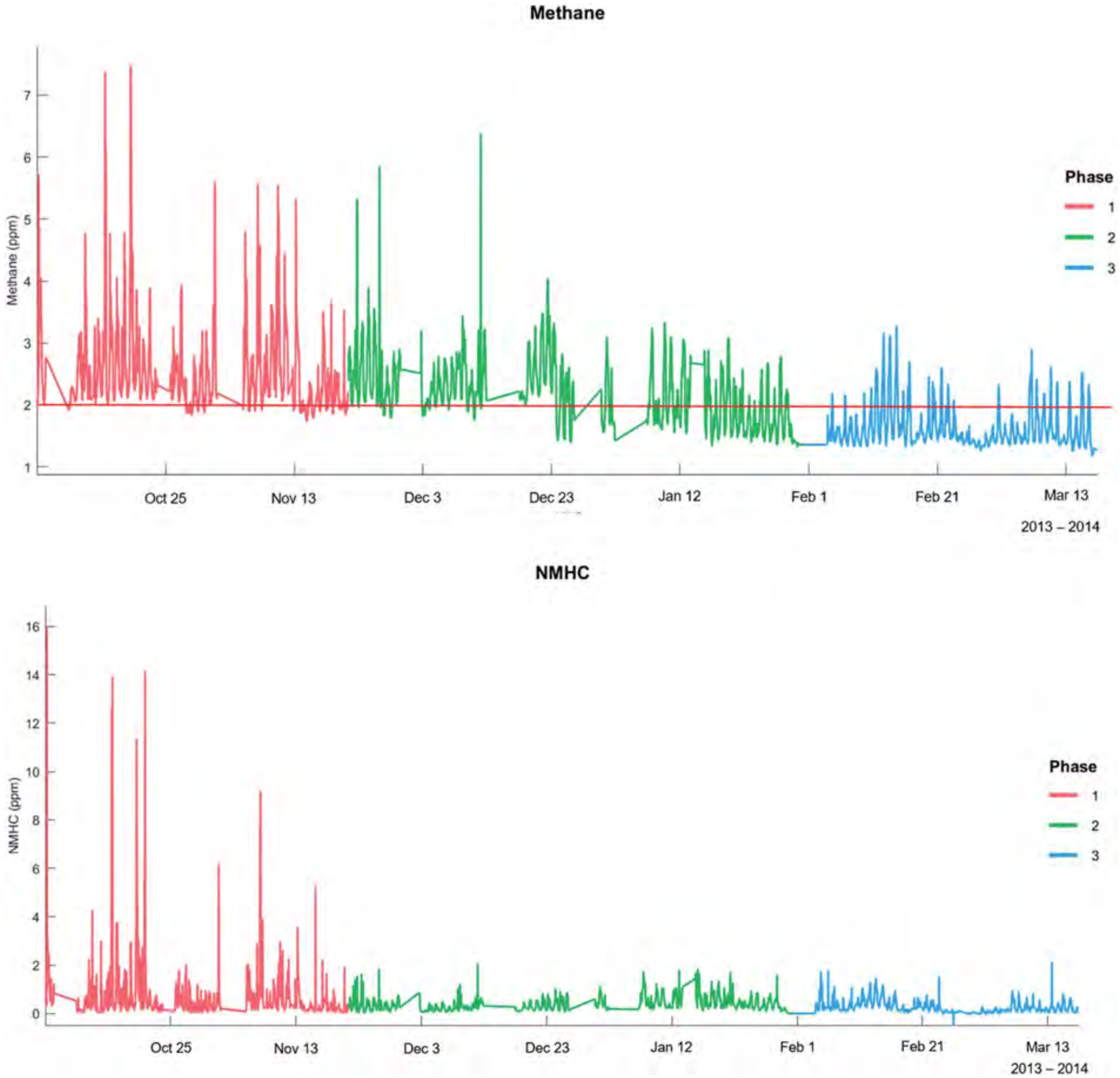

Fig. 2 Hourly averaged non-methane hydrocarbon and methane ambient air concentrations (ppm) at fenceline monitor separated by Phase 1 (active production) Phase 2 (maintenance) and Phase 3 (idle) periods from October 2013–March 2014. Red horizontal line is placed at 2.0 ppm for methane as a reference.

phases (Fig. 3). Ambient methane concentrations typically follow a diurnal pattern, whereby concentrations usually peak around dawn, largely driven by patterns in the planetary boundary layer.[45] During the monitoring period we observed this pattern, however methane concentrations were enhanced during oil and gas operations (phase 1) when compared with

Table 1 Concentrations of minute-averaged methane and non-methane hydrocarbons measured near the AllenCo oil and gas development site in North University Park neighborhood in Los Angeles, California

	Methane (ppm)			NMHC (ppm)		
Phase	Mean (sd)[a]	Median [25th, 75th]	Range	Mean (sd)[a]	Median [25th, 75th]	Range
1	2.53 (1.03)	2.25 [2.05, 2.67]	1.79–37.54	0.69 (2.77)	0.20 [0.07, 0.50]	0–157
2	2.15 (0.77)**	2.09 [1.74, 2.46]	0–48.32	0.30 (0.49)**	0.25 [0.14, 0.48]	0–39.61
3	1.68 (0.35)**	1.47 [1.38, 1.67]	0–6.09	0.24 (0.50)**	0.16 [0.06, 0.32]	0–31.76
Overall	2.08 (0.84)	1.99 [1.53, 2.35]	0–48.32	0.43 (1.55)	0.21 [0.09, 0.43]	0–157

[a] Wilcoxon–Mann–Whitney test between Phase 2 and 3 compared to Phase 1 (active) operations; * $p < 0.05$ ** $p < 0.01$.

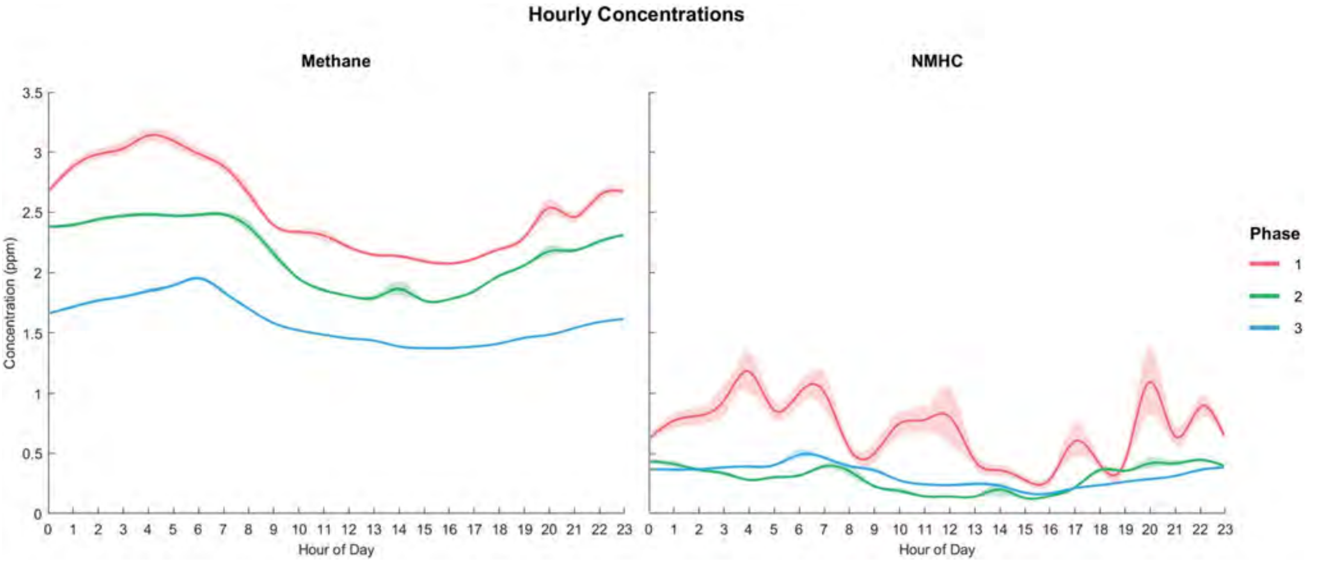

Fig. 3 Methane concentrations averaged by time of day and AllenCo operation phase (October 2013–March 2014). Note that this figure uses Pacific standard time rather than local time; approximately the first month of phase 1 and the last week of phase 3 would have occurred during daylight savings time. Oil and gas operations, traffic, and other human activities were shifted by one hour more than halfway through phase 1, creating inconsistency in the analysis. Therefore time was standardized.

the idle period (phase 3), with baseline concentrations dropping with each successive phase. For NMHC, we observed an inconsistent pattern during active oil and gas production, where concentrations peaked in early morning hours, mid-day and then after sundown. Concentrations throughout phases 2 and 3 were more similar to patterns observed near traffic but away from oil and gas in Los Angeles, where NMHC levels rose during the night and morning rush hour.[45,46] Elevated levels of NMHC can lead to diminished air quality as they are precursors to photochemical ozone formation and secondary organic aerosols.

Statewide comparison

To assess whether difference across the three phases could be explained by seasonal differences of the phases, we plotted the methane data from monitors near the well pad with measurements collected by the California Air Resources Board (CARB) during the same time period in Fig. 4.[47] Across California, anthropogenic emission sources of CH_4 include ruminant livestock, landfills, wastewater treatment, oil and gas extraction and transmission, combustion of fossil fuels and biomass, and rice cultivation, therefore we included multiple monitor stations for comparison.[44] The measurements from the CARB monitor locations did not suggest significant decreases across the phases, in contrast to the observations near AllenCo. During phase 3, we observed measurements similar to those from the comparison CARB sites. This further supports that that the differences in ambient concentrations across phases were driven, in part, by changing operations at the facility. A monitor located approximately a mile away from AllenCo on USC's campus is also included in this comparison (noted at Los Angeles (USC) site in Fig. 4). While this data was collected in 2015 after the site's closure and not available for the study period, we have included the corresponding months in our analysis to show a baseline for the same urban area in the absence of oil and gas activities.

Integrated canister sampling

Results from analysis of triggered grab samples and passive 24 hour sampling during active and idle periods are summarized in Table 2. The concentration trends for the selected gaseous compounds known to be associated with well stimulation and production[23,34] were compared to the Los Angeles Annual Air Toxics Summary from CARB[48] and the Multiple Air Toxics Exposure IV Study conducted by SCAQMD.[49] Mean concentrations during active operations of benzene exceeded levels measured in the Los Angeles County region, but did not exceed the state acute reference exposure level. On average, speciated sampling demonstrated a decrease in fenceline air pollution, with a 32%, 28% and 69% decrease in benzene, toluene and *n*-hexane concentrations respectively after production at the site idled. Natural gas markers, including ethane, propane and *n*-pentane, also all decreased by over 50% after production ceased. The triggered samples during operation suggest that episodic releases include multiple hazardous air toxics with benzene and toluene concentrations several times higher than the comparison values based on regional studies. Elevated levels of xylenes were also observed during trigger events compared to regional concentrations.

Source-apportionment

The neighborhood is proximate to two major freeways, which likely contributed to the observed VOC concentrations. Propane, *n*-butane and *n*-pentane are emitted in relatively small

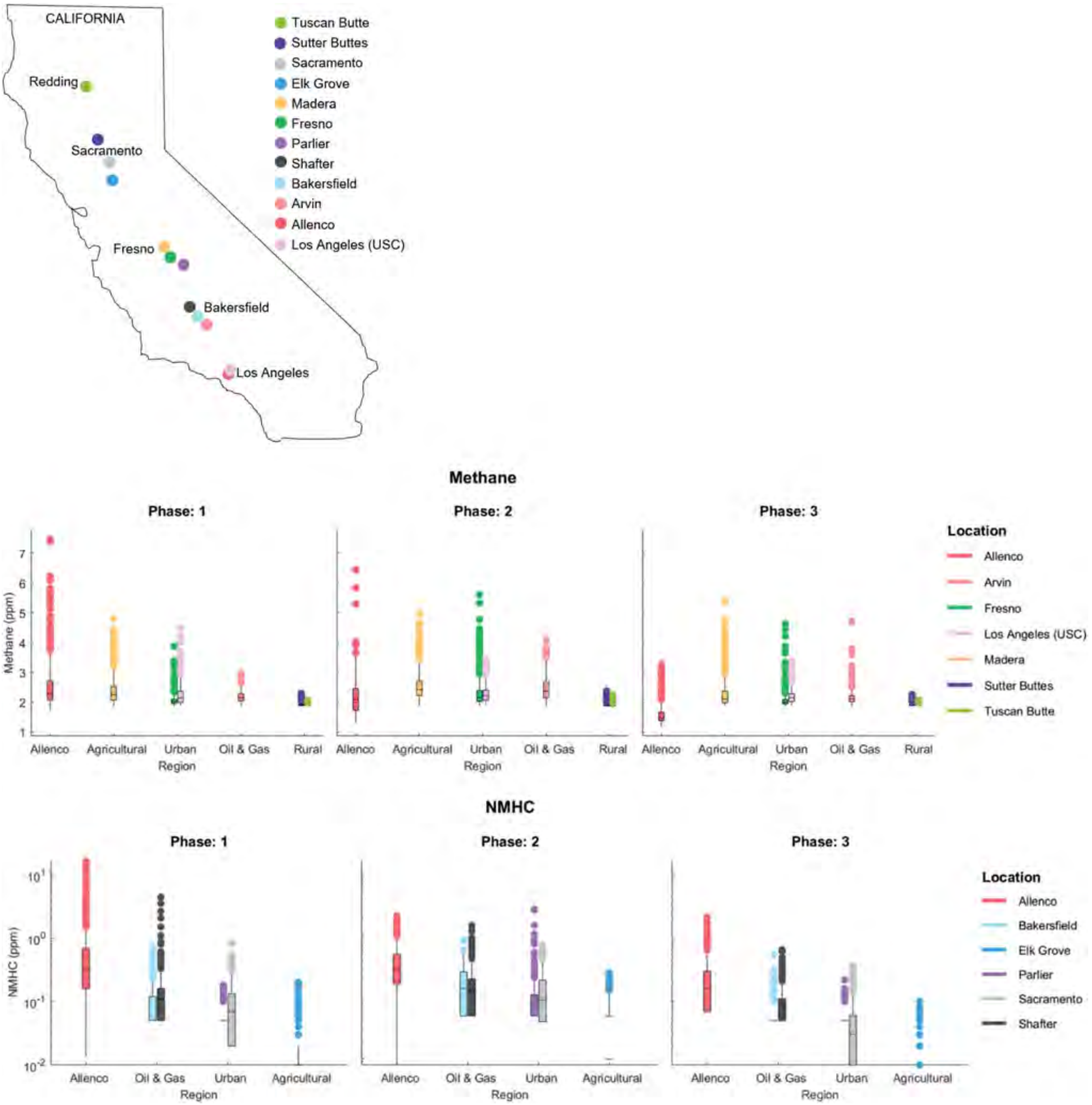

Fig. 4 Comparison of concentrations measured at the fenceline of the AllenCo oil and gas facility with measurements from monitors in California from California Air Resources Board separated by Phase 1 (active production) Phase 2 (maintenance) and Phase 3 (idle) periods from October 2013–March 2014. The box plots show the median and box displays the interquartile range, the points are outliers that exceed 1.5 times the interquartile range.

amounts from traffic sources compared with natural gas sources. In contrast, traffic-related emissions are the primary source of acetylene. In Fig. 5 we show a series of scatterplots with trendlines comparing the relationship during active (n = 17) *versus* idle (n = 98) operations using passive canister data. Phase 1 is shown in red while phase 3 is shown in blue. Full correlation matrix is provided in the ESI (Fig. S2 and S3†). We found a strong correlation between propane and *n*-butane (Pearson correlation, r = 0.94) and *n*-pentane (r = 0.95) during the active phase, which weakened during the idle period (r = 0.67 and 0.69 respectively). In contrast, benzene remained correlated with both propane and acetylene across all phases. Among the 5 minute trigger samples taken during active operations, we found moderate correlations between propane and some hazardous air pollutants such as *n*-hexane (r = 0.96), toluene (r = 0.94), benzene (r = 0.58) and *mp*-xylenes (r = 0.43) (ESI Fig. S4†).

Table 2 Triggered and 24 hour mean and standard deviation of speciated canister samples (ppbv) during active and idle operation periods. Concentrations are compared to other measurements near downtown Los Angeles, California

	Passive samples (24 hours)[a]		Triggered samples[a] (5 minutes)	Comparison concentrations		
VOC species (ppb)	Active operation (n = 17)	Idle operation[c] (n = 98)	Active operation (n = 44)	CARB[48] (2013)	MATES IV[49] (2012–2013)	OEHHA reference exposure levels[b]
Ethane	21.79 (17.60)	9.88** (5.94)	446.01 (707.37)	N/A	N/A	N/A
Ethylene	3.10 (1.71)	2.19* (1.45)	7.43 (6.58)	N/A	N/A	N/A
Acetylene	2.35 (1.29)	1.69* (1.05)	5.26 (4.39)	N/A	N/A	N/A
Propane	21.94 (15.23)	5.72** (4.52)	601.40 (816.12)	N/A	N/A	N/A
n-Butane	7.18 (5.68)	1.78** (1.67)	240.39 (327.16)	N/A	N/A	N/A
n-Pentane	2.29 (1.71)	0.70** (1.13)	59.37 (69.30)	N/A	N/A	N/A
Isoprene	0.21 (0.17)	0.14 (0.29)	0.34 (0.37)	N/A	N/A	N/A
n-Hexane	0.80 (0.74)	0.23** (0.14)	14.42 (16.88)	N/A	N/A	N/A
n-Heptane	0.45 (0.50)	0.12** (0.08)	5.68 (7.03)	N/A	N/A	N/A
Benzene	0.50 (0.32)	0.30** (0.17)	4.18 (4.61)	0.378 (0.187)	0.40 (0.21)	8.46
Toluene	1.14 (0.83)	0.69** (0.47)	5.95 (6.61)	1.02 (0.71)	1.15 (0.70)	9824.3
Ethylbenzene	0.17 (0.08)	0.10** (0.07)	0.60 (0.59)	0.41 (0.16)	0.72 (0.74)	460.9 (c)
mp-Xylenes	0.62 (0.46)	0.33** (0.23)	3.19 (3.53)	1.60 (0.61)	2.50 (2.48)	5069.6
o-Xylene	0.24 (0.19)	0.13** (0.08)	0.76 (0.75)	0.47 (0.18)	0.52 (0.52)	5069.6
Styrene	0.13 (0.07)	0.09* (0.06)	0.35 (0.38)	0.06 (0.03)	0.03 (0.04)	4933
n-Octane	0.21 (0.23)	0.06** (0.06)	1.91 (2.51)	N/A	N/A	N/A
n-Decane	0.15 (0.10)	0.04** (0.02)	0.31 (0.26)	N/A	N/A	N/A

[a] Wilcoxon–Mann–Whitney test between active and idle operations; * $p < 0.05$, ** $p < 0.01$. [b] California Office of Environmental Health Hazard Assessment (OEHHA) provides acute reference exposure levels (RELs) are provided in μg m^{-3} and converted to ppbv for comparison using standard temperature and pressure. If acute values were unavailable, chronic values were calculated and indicated with a (c). N/A is unavailable. [c] Summarized for the passive canisters at the KS Park location.

Positive matrix factorization

The analysis to better ascertain sources of VOCs in the neighborhood revealed six source factors (Fig. 6). The first factor "Combustion" is characterized by high loadings of the aromatics; *mp*-xylene, *o*-xylene together with heavier alkanes which are often indicative of diesel equipment or combustion engines. The second factor "Aged Motor Vehicle Emissions" consists primarily of the alkane ethane, which may represent aged air mass.[50] This factor also has high loadings of ethylene, acetylene, and benzene which can be attributed to motor vehicle emissions.[51–54] Acetylene is emitted primarily by automobile exhaust;[55,56] similarly we see ethylene, acetylene, benzene, and toluene as primarily contributors to the third factor "Motor Vehicle Emissions".[52–54,57] Isoprene is useful in identifying a biogenic signal and as the strongest contributor to fourth factor, this has been identified and labeled as the "Biogenic" source factor.[58,59] The fifth factor is characterized by high loadings of styrene, which is primarily used in industrial manufacturing.[60,61] Styrene has been also identified at the fenceline of oil and gas well pads in Colorado,[62,63] while an analysis in Texas associated styrene factor with nearby plastics manufacturing facility.[64] Factor six was interpreted as the "Natural Gas" source factor due to high loadings of propane, ethane, *n*-butane, and *n*-pentane.[50,65] These light alkanes are sourced predominantly from oil and gas operations and related industries, and do not constitute a large fraction of urban or vehicle emissions.[66] Furthermore, we see different contributions of PMF-resolved sources to total measured VOCs by phase (Fig. 7).

Globally, biogenic emissions, such as isoprene dominate the organic carbon budget, while anthropogenic emissions comprise ~15%.[67] The key anthropogenic sources include oil and natural gas operations, gasoline storage and transportation, combustion (*e.g.* traffic), chemical manufacturing and solvent use.[68] Traffic-related emission typically dominate the VOC mixture in urban environments.[69] VOCs including benzene and *n*-hexane are predominately emitted from anthropogenic sources such as evaporating fuel or incomplete combustion. Oil and gas development regions have been characterized by large emissions of light alkanes.[70,71] Vented and fugitive emissions of methane that occur at oil and gas production sites may raise concerns due to co-emission of hazardous air pollutants.[54,55] We leveraged a unique opportunity to assess neighborhood air quality during active and idle phases of an urban drill site situated in a community burdened by multiple sources of air pollution. The "Natural Gas" emissions PMF-resolved source contributed 23.7% to the total measured VOCs measured in November 2013 during the active phase, and only 0.6% to the total measured VOCs in November 2015 during the idle phase. This provides additional evidence in changes neighborhood air quality during the idling of the oil and gas facility.

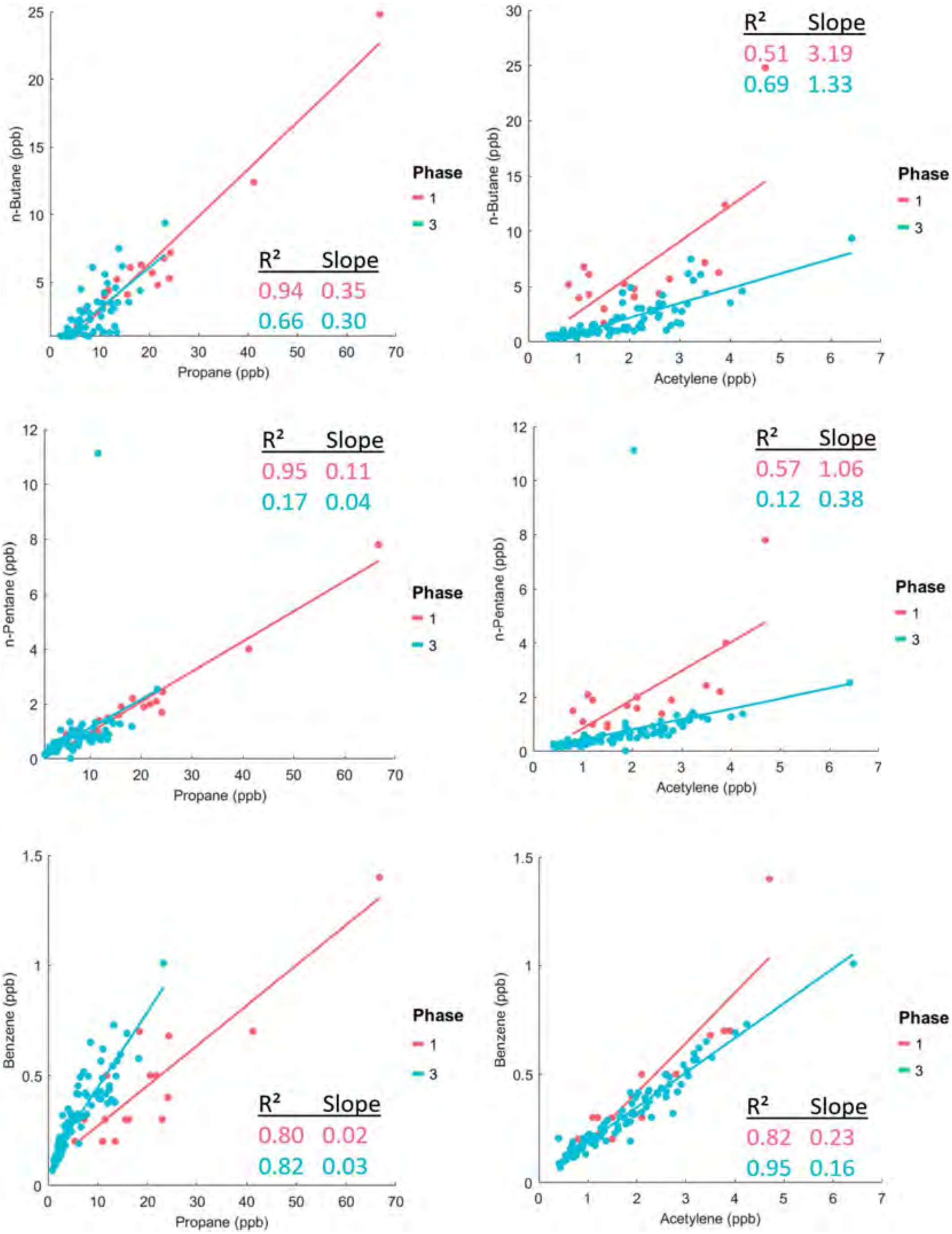

Fig. 5 Correlation plots of *n*-butane, *n*-pentane and benzene with propane (oil and natural gas tracer on left) and acetylene (traffic/combustion tracer on right) during active and idle period of the oil and gas development facility. Coefficient of determination, R^2, values are shown for each phase.

Our analysis of the data collected by the local air district, SCAQMD, suggest that changes in production at an urban oil-field site significantly impacted concentrations of both methane and non-methane hydrocarbons at in the adjacent neighborhood, even in an urban air with known poor air quality. The environmental impacts of upstream oil and gas development are recognized[3,72,73] as an ongoing focus to assess atmospheric emissions of methane and other organic pollutants as well as their potential impact.[16,17,62,74,75] According to the California greenhouse gas inventory, the oil and gas sector is the largest industrial source of methane emissions, constituting approximately 16% of the total methane emissions in the state.[47] Emissions from well pads can be difficult to measure and model due to temporal variability and the large number of potential sources, such as fugitive emissions of storage tanks or pipes or episodic events like acidization. Well

Fig. 6 Source profiles for the six factors resolved by positive matric factorization of volatile organic compounds (VOCs) for the passive canister samples at the fenceline of the oil development facility.

pad emissions can also vary over time as wells age and production levels and pressures change.

The results suggests that a broad range of hazardous air pollutants are co-emitted during active operations, and these compounds may be biologically additive or act synergistically in the human body, near a vulnerable population. This research contributes to a body of evidence demonstrating impacts of air quality due to oil and gas operations and adds to the literature

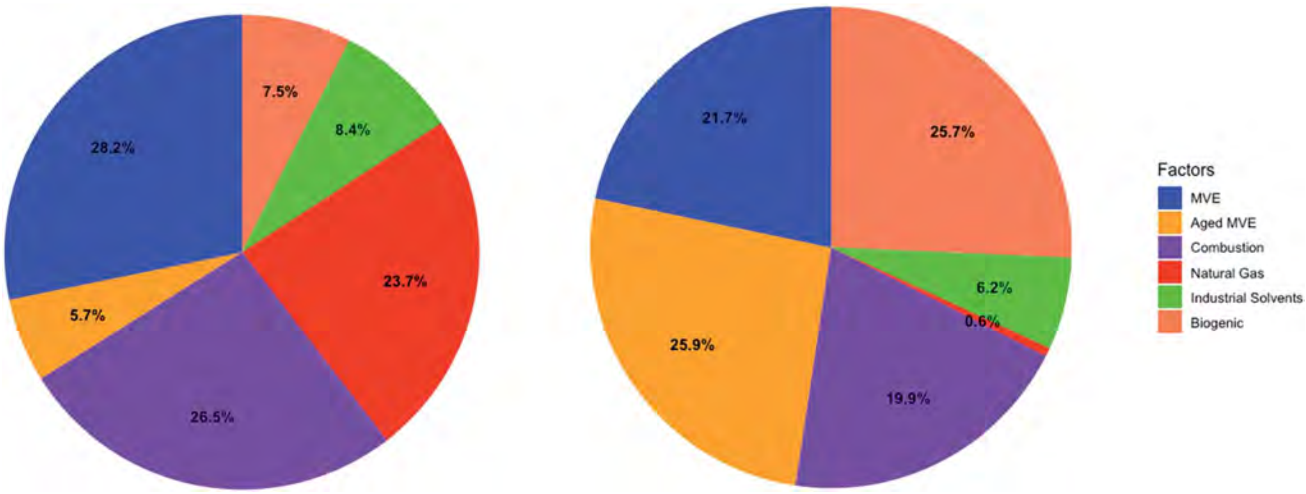

Fig. 7 Volatile organic compounds (VOCs) contribution of PMF-resolved sources by active (left, November 2013) and idle (right, November 2015) phase of oil and gas production.

in urban environments with complex mixtures. Epidemiological research has demonstrated adverse health impacts in such communities,[29,76] despite concentrations of air pollutants often below regulatory thresholds.[23] For example, research suggests that adverse impacts of benzene are observed at concentrations below permissible limits.[77–79] The fenceline community near the AllenCo facility is home to over 90% people of color (self-identify as Hispanic and/or as a race other than White) and approximately three-quarters of households live below 200% of the federal poverty line.[29] According to CalEnviroScreen, CA's environmental justice screening tool to identify highly vulnerable communities, this area is among the top 10% most disproportionately–environmentally burdened in the state.[80] A recent study in South Los Angeles neighborhood identified wheeze and lower lung function among residents living closer to oil wells.[76] Air pollution may be an important factor contributing to the observed health disparities. Understanding the neighborhood scale impacts to air quality and human health is important for improving public health protections, particularly in urban environments such as Los Angeles.

Previous community-scale studies have looked at concentrations of air pollutants in urban communities around oil and natural gas operations.[17,81,82] One previous study in Los Angeles analyzed benzene, *n*-hexane, and *n*-pentane concentrations near an active oil and gas production site to determine the impact from the oil site in an urban community with many emission sources contributing to poor air quality.[81] Another study in Los Angeles found elevated baseline and larger spikes of methane and NMHC nearby oil and gas facilities and distribution pipelines as opposed to other areas in the community.[46] The AllenCo site itself still appeared to emit fugitive methane approximately three years after the site's closure.[75] Studies in Colorado identified higher benzene and toluene concentrations near a well pad when compared to a highly trafficked urban location.[83,84] Macey and colleagues used community-based sampling to measure chemical concentrations near unconventional oil and gas operations and found that BTEX compounds as well as *n*-hexane exceeded chronic risk levels.[82] Documented health effects from exposure to such chemicals include symptomatic acute physical and respiratory effects, dizziness, headaches, and fatigue at lower exposures, numbness in the limbs, incoordination, and tremors, and respiratory system irritation, including difficulty breathing, and impaired lung function.[85] A systemic review suggests that the production phase has the potential to emit the highest concentrations and the most varied mixture of hazardous air pollutants.[17]

This study is limited by the type and length of ambient air monitoring with only 6 weeks of available data during active operations. Additional historical data could have provided a clearer picture of air quality near the site during multiple seasons and operations for a more in-depth comparison. VOC concentrations measured at and near the fenceline likely depend on numerous factors, meteorological conditions, background concentrations, oil and gas composition and production rates, and other on-site activities. Maintenance issues (*e.g.*, fugitive leaks, open or leaking thief hatches, failed pressure relief devices, malfunctioning separator dump valves) are more prevalent at smaller, older production sites and may contribute to the observed ambient air concentrations. Nonetheless, this is one of the first analysis to compare neighborhood air quality during active and idle oil and gas development in an urban environment. Reductions in ambient BTEX, *n*-hexane, *n*-pentane, ethane, and propane were observed after production ceased at the fenceline.

Conclusions

The idling of the oil and gas site in South Los Angeles offers a unique opportunity to understand changes to neighborhood air quality in an urban area with oil drilling. In urban environments, existing data are insufficient to answer questions regarding the contributions of oil and gas production to neighborhood air quality, due to the scarcity of regulatory monitoring and the unreliability of self-reported emissions data. Across Los Angeles, there are approximately 5000 active or idle oil and gas wells. Nearly half of these active wells operate less than 150 meters from residential homes.[29,76] Chemicals and operations associated with upstream oil and gas development pose threats to humans, climate and ecosystem health.[3,73,86] As the upstream oil and natural gas sector continues to grow, it is increasingly a major source of methane and light non-methane hydrocarbons in the US. Emissions of methane and NMHC has been seen with respect to oil and gas development as a result of venting, flaring, and leakage in oil and gas region.[37,87] The results of this study suggest that active oil and gas development impact neighborhood air quality in the urban environment of South Los Angeles. Future research and regulatory efforts should focus on ambient air quality near urban oil drilling sites and methods to reduce emissions.

Conflicts of interest

We declare no conflict of interest.

Acknowledgements

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Exhibit 38.08

This exhibit was not previously submitted in November 2023

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Estimating Emissions of Toxic Hydrocarbons from Natural Gas Production Sites in the Barnett Shale Region of Northern Texas

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Supporting Information

ABSTRACT: Oil and natural gas operations have continued to expand and move closer to densely populated areas, contributing to growing public concerns regarding exposure to hazardous air pollutants. During the Barnett Shale Coordinated Campaign in October, 2013, ground-based whole air samples collected downwind of oil and gas sites revealed enhancements in several potentially toxic volatile organic compounds (VOCs) when compared to background values. Molar emissions ratios relative to methane were determined for hexane, benzene, toluene, ethylbenzene, and xylene (BTEX compounds). Using methane leak rates measured from the Picarro mobile flux plane (MFP) system and a Barnett Shale regional methane emissions inventory, the rates of emission of these toxic gases were calculated. Benzene emissions ranged between 51 ± 4 and 60 ± 4 kg h^{-1}. Hexane, the most abundantly emitted pollutant, ranged from 642 ± 45 to 1070 ± 340 kg h^{-1}. While observed hydrocarbon enhancements fall below federal workplace standards, results may indicate a link between emissions from oil and natural gas operations and concerns about exposure to hazardous air pollutants. The larger public health risks associated with the production and distribution of natural gas are of particular importance and warrant further investigation, particularly as the use of natural gas increases in the United States and internationally.

■ INTRODUCTION

In recent years the development of energy from unconventional oil and natural gas (ONG) sources has grown substantially and has been hailed by some as an effective CO_2 mitigation strategy.[1] However, the fugitive emissions associated with the production and distribution of natural gas are atmospherically relevant and can potentially have large short-term climate impacts.[2−5] Methane (CH_4), the primary component of natural gas, has a global warming potential 86 times greater than CO_2 on a 20 year time scale and 34 times greater on a 100 year time scale.[6] In addition to the climatological impacts, ONG activities can have an effect on local air quality and potentially on human health. Increased CH_4 in the atmosphere can lead to the formation of surface ozone, meaning its impacts are felt on both regionally and on a global scale.[7] Throughout the past decade, advances in horizontal drilling and hydraulic fracturing have made extraction of natural gas from these tight shale formations viable. In some instances, shale gas operations are in close proximity to densely populated areas. This has led to growing public concerns and numerous studies regarding exposure to hazardous air pollutants (HAPs).[8] These HAPs include gases such as hexane, 1,3-butadiene, benzene, toluene, ethyltoluene, and isomers of xylene (BTEX compounds), some of which can lead to minor health effects with short-term exposure or can potentially be carcinogenic with prolonged exposure.[9−12] While results of these studies show varying implications of these emissions, some studies have suggested a link between increased health risks and proximity of residents to ONG extraction and processing sites.[13−15]

The Barnett Shale of northern Texas is one of the most developed and productive ONG reservoirs in the United States. The region, which covers 5,000 square miles, is home to over 30,000 active conventional oil and natural gas wells (Figure 1).[16] During peak production in 2012, nearly 6 billion cubic feet (Bcf) of natural gas were produced per day, while a maximum of 4,600 barrels (Mbbl) of oil were generated daily in 2013.[17] As of 2015, the region is still responsible for roughly six

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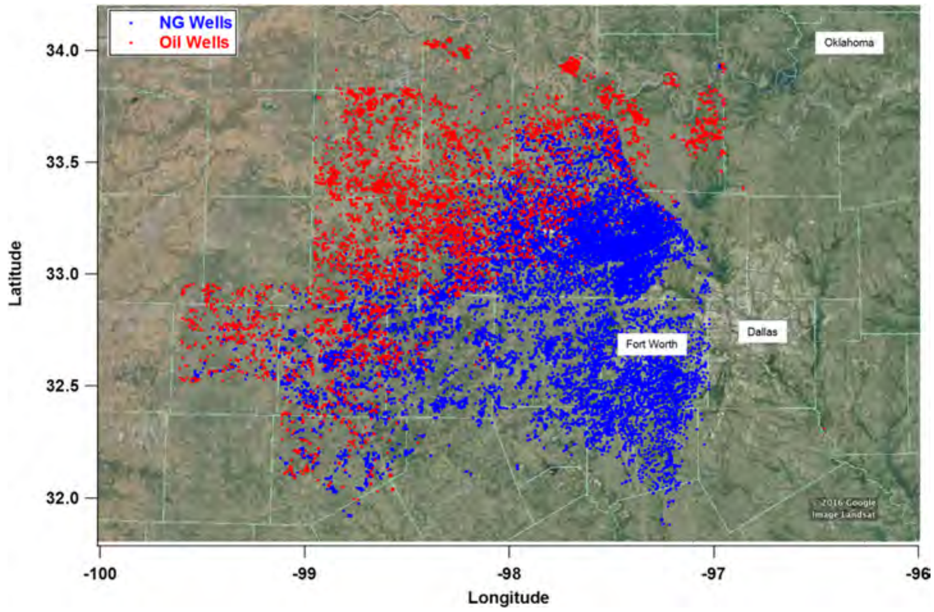

Figure 1. Map showing the location of oil and natural gas wells in the Barnett Shale region, with natural gas wells highlighted in blue and oil wells in red. Locations of the well sites obtained from Drillinginfo.[16]

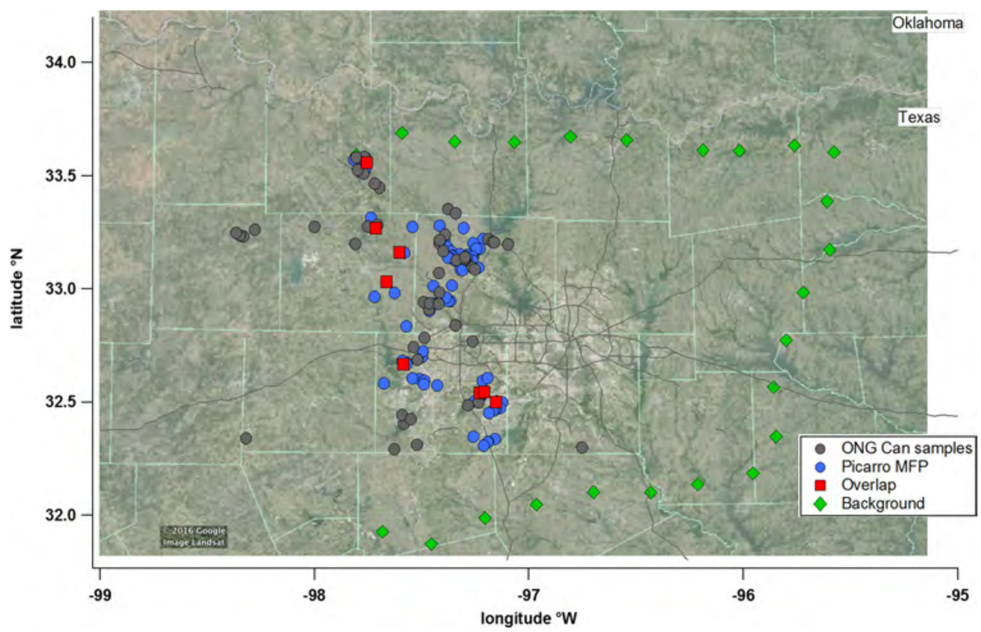

Figure 2. Map of the Barnett Shale region showing whole air canister sample locations (gray) and natural gas well pads sampled by the Picarro Mobile Flux Plane (blue). At 8 locations, the two measurements were collected concurrently (highlighted in red). Background canister sample sites are shown in green.

percent of the nation's natural gas.[18] In addition to its large ONG infrastructure, the Barnett Shale is situated within one of the most populated regions in the country. Nearly 3 million people live within the production area, with the cities of Fort Worth and Arlington also contained within the core natural gas producing counties (Denton, Johnson, Tarrant, Wise).[17,19] Similarly to other ONG fields in the US, the proximity of this large residential population to oil and gas operations has intensified concerns about the potential health impacts of exposure to VOCs emitted from these sources.[20] In addition, this area (including the 4 core counties) is also designated as a moderate nonattainment area for exceeding the 2008 National Ambient Air Quality Standard for 8-h ozone of 75 ppb.[21] With the current 8-h standard reduced to 70 ppb, it is possible that exceedances may become more common in the region.

The natural gas industry now serves as the largest anthropogenic source of CH_4 nationally[22] and has long been regarded as a source of hydrocarbon pollution.[23] Consequently, recent studies have focused on more accurate quantification of CH_4 emissions from the natural gas industry in various shale plays across the United States.[24−27] However, accurate quantification has proven difficult, with studies varying widely in CH_4 estimates and large discrepancies occurring between top-down and bottom-up approaches.[28,29] The Barnett Coordinated Campaign was conducted from October 16−30, 2013, and consisted of multiscale measurements to quantify

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Table 1. Average Mixing Ratios Observed in Well Mixed Air and Downwind of Oil and Natural Gas Sources in the Barnett Shale[a]

	CH_4 (ppmv)	hexane (C_6H_{14})	benzene (C_6H_6)	toluene (C_7H_8)	ethylbenzene (C_8H_{10})	*m*/*p*-xylene (C_8H_{10})	*o*-xylene (C_8H_{10})
background (n = 24)	1.95 (0.07)	200 (140)	100 (44)	150 (110)	20 (15)	66 (44)	22 (18)
oil wells (n = 12)	4.33 (4.27)	9710 (18300)	820 (1300)	2310 (5270)	140 (240)	2600 (7770)	310 (760)
NG wells (n = 31)	4.35 (5.87)	3210 (9400)	290 (500)	590 (1190)	56 (130)	510 (1460)	86 (200)
dry gas (n = 17)	6.36 (7.20)	860 (1310)	230 (320)	360 (430)	50 (75)	200 (280)	60 (80)
wet gas (n = 35)	4.60 (5.55)	6780 (13700)	590 (940)	1360 (3170)	100 (180)	1360 (4520)	180 (470)
compressor stations (n = 10)	8.12 (7.85)	3700 (5840)	610 (800)	910 (1080)	100 (130)	550 (730)	120 (100)
distribution and storage (n = 5)	3.89 (0.51)	530 (410)	170 (10)	230 (90)	50 (49)	180 (240)	50 (60)
gathering and processing (n = 3)	2.43 (0.45)	590 (240)	130 (70)	270 (120)	25 (8)	90 (30)	34 (10)
fracking wells (n = 2)	2.10 (0.05)	690 (100)	190 (90)	770 (680)	55 (25)	150 (80)	51 (40)

[a]Wet and dry gas wells were distinguished based on %C_2H_6. 1σ standard deviation shown in parentheses. Units for all compounds are in pptv unless otherwise noted.

CH_4 emissions from the various sources in the region, including whole air sampling.[30] Unlike hydrocarbon measurements at regional monitoring locations, whole air samples were collected downwind of individual ONG sites, providing a snapshot of emissions. Our previous work using the same samples paired alkane and stable isotope ratios of CH_4 sources in the region with a bottom-up inventory to aid in comparison to top-down CH_4 estimates.[31] Presented here are measurements and emissions estimates of *n*-hexane and the BTEX compounds for the greater Barnett Shale region, utilizing the VOC to CH_4 ratios determined from whole air samples combined with mobile flux measurements and a bottom-up CH_4 emissions inventory.

■ METHODS

Whole Air Samples. During October 2013, whole air samples were collected downwind of various thermogenic CH_4 sources throughout the Barnett Shale (one sample at each location). Oil and natural gas (ONG) sample locations included natural gas well pads (n = 31), some of which housed separators, condensate tanks, or compressors in addition to the well heads; conventional oil wells (n = 12); compressor stations (n = 10); distribution city gates (where gas is held before delivery to consumers) and storage facilities (n = 5); and gathering and processing facilities (n = 3). In addition, "background" samples representative of well mixed air in the Barnett shale, both up and downwind, were collected away from point sources. Sample locations, primarily focused on the western edge of the Barnett Shale, are shown in Figure 2. Sample collection was guided by a Picarro Instruments G2301, powered by a vehicle alternator, which analyzed CH_4, CO_2, and H_2O. Downwind of point sources, the GHG analyzer was used to detect enhancements in CH_4 of at least 50 ppb over typical ambient CH_4 concentrations on that day, with the instrument inlet located upwind of the vehicle. Conversely, on the day in which regional background samples were collected, the analyzer was used to ensure that no enhancements in ambient CH_4 were observed before a canister was filled.

Whole air samples were collected in 2 L electropolished stainless steel canisters, evacuated to a pressure of 10^{-2} Torr. Canisters were preconditioned before sampling, by baking at 150 °C and flushing with ultrahigh purity helium. Air samples were then returned to the University of California, Irvine for analysis on a multicolumn, multidetector gas chromatographic system, described in detail elsewhere.[32] Trace gases measured include CO, CO_2, CH_4, and other C_2−C_{10} hydrocarbons (alkanes, alkenes, aromatics), of which only unbranched alkanes and BTEX compounds were utilized in subsequent calculations. The limit of detection for hydrocarbons is 3 parts per trillion (pptv), with analytical precision and accuracy of 3% and 5%, respectively. VOCs are calibrated to NIST traceable absolute hydrocarbon standards or in-house standards that have undergone extensive intercomparison.[33,34]

Methane Flux Measurements. Methane emissions from well pads were quantified utilizing the Mobile Flux Plane (MFP) method, as described by Rella et al.[35] Briefly, a vehicle outfitted with a GPS, anemometer, and CH_4 analyzer is driven on the downwind side of a well pad. Ambient CH_4 is measured through a series of vertical inlets from the base of the vehicle to a height of approximately 4 m above ground. Sample reanalysis of CH_4 is triggered upon detection of a plume and along with position and vertical wind speed, the emission rate is calculated (kg h^{-1}). At an average distance of 34 m, the detection limit is 0.034 kg h^{-1} and measurement accuracy is 24%.[35] At some ONG well pads (n = 8), MFP measurements and whole air samples were collected concurrently (Figure 2), allowing for a full hydrocarbon profile to be obtained along with CH_4 fluxes.

Methane Emissions Inventory. Regional emissions from the various CH_4 sources in the Barnett Shale were estimated through a spatially resolved inventory developed by Lyon et al.[29] In summary, experimental data collected at ONG sites throughout the area were used along with national data on gathering and processing facilities to categorize the sources. Emission factors accounting for the fat-tail distribution (few sites with large emissions) were then calculated and used to determine overall CH_4 inventory estimates.[29] The inventory estimated that approximately two-thirds of total CH_4 emissions are from thermogenic (ONG) sources.

■ RESULTS AND DISCUSSION

Ambient Mixing Ratios and Hydrocarbon Composition. Average mixing ratios of CH_4 and select hydrocarbons determined from whole air samples of background air and downwind of ONG wells are summarized in Table 1. An in-depth characterization of the light alkanes associated with thermogenic CH_4 sources is presented in Townsend-Small et al.,[31] and the primary focus of the current study is the toxic VOCs. For each of the ONG sources sampled in this study, VOCs were enhanced from 2 to nearly 50 times over background (Table 1). For similar CH_4 values, conventional oil wells generally showed higher concentrations than natural gas well pads for each of the hazardous air pollutants,

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Table 2. Hydrocarbon Composition As Described by Average Percentage of Alkane and Aromatic Compounds Present in All Source Types Sampled in the Barnett Shale[a]

	CH_4 (%vol)	C_2H_6 (%vol)	C_3–C_5 (%vol)	n-C_6H_{14} (%vol)	BTEX (%vol)	BTEX (%mass)
conventional oil	77.5 (7.0)	9.7 (2.2)	12.3 (2.8)	0.4 (0.2)	0.2 (0.2)	0.79
natural gas wells	87.6 (11.0)	6.5 (4.7)	5.7 (4.5)	0.2 (0.1)	0.1 (0.1)	0.38
compressor stations	87.8 (16.8)	5.2 (3.1)	6.7 (5.8)	0.2 (0.3)	0.1 (0.1)	0.42
gathering and processing	93.8 (4.9)	3.5 (2.1)	2.6 (1.3)	0.1 (0.1)	<0.1	0.15
distribution and storage	95.9 (1.5)	3.3 (1.5)	0.8 (0.5)	<0.1	<0.1	0.08
dry ONG					<0.1	0.29
wet ONG					0.1 (0.1)	0.58
ERG ONG[37]						1.36

[a]For butane and pentane, both the iso- and n-isomers were included in calculations (for a total of 13 compounds).

Table 3. Methane Fluxes Measured by the MFP System and Corresponding Mixing Ratios from Canister Samples Filled Concurrently[a]

MFP CH_4 flux (kg/h)	CH_4 (ppmv)	C_6H_{14} hexane	C_6H_6 'B'	C_7H_8 'T'	C_8H_{10} 'E'	C_8H_{10} m/p-'X'	C_8H_{10} o-'X'
0.26	5.008	91	80	81	10	31	13
0.82	2.437	5425	465	450	54	180	51
2.92	2.040	410	160	220	16	86	20
3.71	2.937	340	240	1080	78	300	140
3.77	5.033	110	73	110	26	94	30
4.97	3.719	6850	510	730	45	610	93
6.94	16.94	55900	3470	17710	800	26000	2580
13.78	15.23	52330	2745	6145	650	6970	1210

[a]CH_4 is reported in ppmv, while the remaining gases are in pptv.

particularly hexane, which was elevated over background by a factor of 48. Measurements taken downwind of natural gas processing facilities showed some of the lowest VOC mixing ratios of the ONG sources, reflecting the removal of higher chained hydrocarbons before the natural gas is distributed to consumers for use. Interestingly, the distribution and storage samples, collected from pipelines, city gates, and a storage facility, did not have the lowest mixing ratios of hydrocarbons listed in Table 1. However, this could be due to conditions at those locations on the sampling date (wind direction, colocation of sources) and not because of increased hexane and BTEX content of natural gas from these sources (Table 2). Natural gas produced in the Barnett Shale is generally "dry", and the composition of distribution and storage samples represents an average of produced gas sources.

Standard deviations (1σ) are also listed in Table 1 and reflect the large variability among well pads from site to site. For reference, minimum, maximum, and median hydrocarbon values for each of the sources are listed in Table S1. The variability is partially due to the geographical and geological makeup of the Barnett Shale, which naturally separates out into regions of drier natural gas (highest CH_4 content), wetter gas (lower CH_4 content), and conventional oil. While not an absolute trend, analysis of the percent composition of light alkanes (C_2H_6 and C_3H_8) illustrated the relationship between geographic location and gas wetness (Figure 5 in Townsend-Small et al.).[31] The highest %C_3H_8 values were found in samples collected in the oil-prone, northwestern portion of the Barnett Shale, while lower percentages were observed at natural gas well pads to the south and east.[31]

Utilizing the percent composition of alkanes, a distinction was made between wet and dry natural gas (Table 1). Samples that contained less than 5% C_2H_6 were classified as "dry", and those with more than 5% C_2H_6 were considered "wet", based on a typical range of C_2H_6 in natural gas of 2–11%.[36] When compared to dry natural gas, wet gas samples exhibited higher average mixing ratios (by a factor of 2–15) for nearly every VOC measured in this study, including the BTEX compounds. Further, in samples collected downwind of well pads producing wet gas, the BTEX content was 2 times greater than dry gas wells (Table 2). A report compiled by the Eastern Research Group (ERG) analyzed VOC content in emissions from oil and condensate storage tanks at 19 different well pads. The average BTEX percentage by mass in the ERG report was 1.36%.[37] By comparison, UCI oil and natural gas samples were 0.29–0.79% BTEX by mass. One possible explanation for this large difference is that condensate storage tanks hold natural gas liquids and often send dry natural gas to other locations, whereas the well pads where canister samples were collected did not all have storage tanks on-site. Another cause for this difference is sampling location − ERG measurements were taken directly at storage tanks and were not affected by atmospheric dilution like the canister samples in this study.

Hydrocarbon composition for each of the ONG sources sampled in this study is summarized in Table 2 (fractions normalized to 13 compounds listed, not total VOCs). Emissions from conventional oil wells were only 77.5 ± 7.0% CH_4 by volume, compared to 87.6 ± 11.0% for natural gas wells, and over 90% in processed natural gas. Likewise, hexane and BTEX composition are highest in oil wells and decrease throughout the natural gas supply chain. Despite higher average mixing ratios when compared to gathering and processing samples (Table 1), distribution gas is indeed the highest quality natural gas (95.9 ± 1.5% CH_4 by volume), containing the lowest levels of alkanes, hexane, or BTEX.

Emissions Estimates of Hazardous Air Pollutants. Methane flux measurements and VOC mixing ratios are listed in Table 3 for the 8 well pads where the MFP captured a plume and canisters samples were collected concurrently (Figure 2). The fluxes ranged from 0.26 kg h^{-1} to 13.8 kg h^{-1}, with the

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largest CH_4 flux values corresponding to the highest ambient mixing ratios of the hydrocarbons measured. The high mixing ratios were observed at wet gas wells (>5% C_2H_6) that also housed compressors and separators, used to separate raw natural gas from condensate (hydrocarbon liquids and water). These results are consistent with helicopter-based infrared camera surveys of ONG wells conducted in various US shale plays.[38] In the Barnett, 21% of well pads with the lowest gas-to-oil ratios (GOR) showed detectable emissions, compared to less than 1% of sites with higher GORs.

Utilizing the VOC to CH_4 ratio and the MFP flux measurements, C_6H_6 emissions, for example, were estimated for the Barnett Shale according to the following equation

$$C_6H_6 \text{ flux} = CH_4 \text{ flux (kg h}^{-1})*(\text{MW } C_6H_6/\text{MW } CH_4)*(C_6H_6{:}CH_4)$$

where C_6H_6:CH_4 is given by the least-squares linear regression fit of the two gases. As seen in Figure 3, for these 8 canister

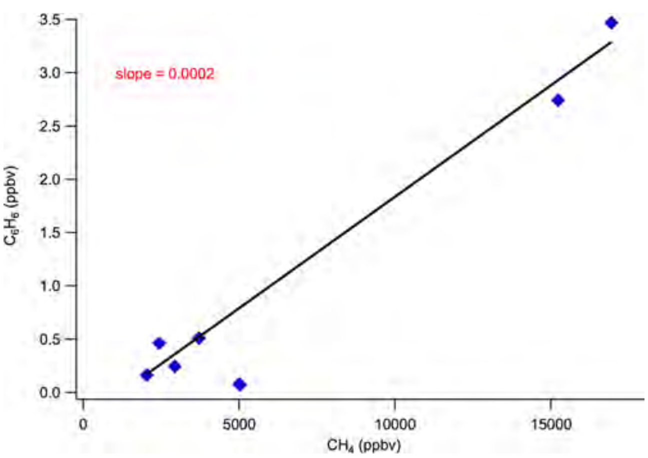

Figure 3. Molar ratio (slope) of C_6H_6 to CH_4 in whole air samples collected concurrently with Picarro MFP flux measurements (n = 8) throughout the Barnett Shale.

samples the molar ratio was 0.0002 ± 2 × 10^{-5}, leading to an average benzene flux of 4.9 ± 1.5 g h^{-1}. Because this value is representative of emissions from an individual well pad, it was then scaled up for the region by the number of actively producing well pads (n = 17,000).[17] Using this method, the overall benzene emission estimate for the Barnett Shale is 84 ± 26 kg h^{-1}. However, this value assumes all well pads in the region have a detectable CH_4 leak rate and is therefore an overestimate of C_6H_6 emissions. Adjusting for the 63% of well pads believed to be leaking in Rella et al.[35] gives an average value of 53 ± 17 kg h^{-1} for the region. The same procedure was carried out for the remaining hazardous compounds of interest. Values are listed in Table 4, all in units of kg h^{-1}. Hexane was by far the most emitted HAP in the Barnett Shale, larger than the BTEX compounds by 1 to 2 orders of magnitude. It should be noted that emissions estimates are affected by the proportion of larger leaks that are sampled. The top 22% of emitters were found to be responsible for nearly 80% of overall well pad emissions.[35] Because canister samples were collected only when sizable leaks were detected, the calculated HAP emissions may be overestimated.

In a second approach for estimating the regional C_6H_6 flux, CH_4 emission rates are taken from the spatially resolved emissions inventory developed for the entire Barnett Shale.[29] Background corrected VOC mixing ratios were used to determine source-specific molar ratios relative to CH_4, as was previously done to estimate regional ethane emissions.[31] Average molar ratios (Table S3) help to lessen biases that arise from sampling only those ONG sites with larger leak rates. These "fat-tail" sites (including well pads, compressors, and processing facilities) contribute roughly 20% of ONG emissions in the region.[29] Overall, the Barnett Shale emits 72,300 kg CH_4 h^{-1}, of which 67% come from thermogenic sources, or 48,400 kg CH_4 h^{-1}. Biogenic sources were not shown to emit significant amounts of heavier alkanes and aromatics, so only the contributions from thermogenic sources are factored into the calculations (Supporting Information). The median emissions estimate is 56 ± 4 kg C_6H_6 h^{-1}. Including low-end and high-end CH_4 estimates (42,100−56,400 kg h^{-1}) gives a range of emissions of 51 ± 4 to 60 ± 4 kg C_6H_6 h^{-1} for the entire Barnett Shale region.

To verify that urban sources (combustion, water treatment plants, landfills) did not overly influence background samples used for mixing ratio corrections, the isopentane to n-pentane ratio was utilized. Previous studies have shown that emissions from vehicular combustion have a higher proportion of isopentane, thus elevating the iso- to n-pentane ratio.[39] For instance, in an urban environment like Pasadena, CA the ratio was 2.41, compared to ONG locations in Colorado such as Wattenberg Field or Erie/Longmont, which had ratios of 0.86 and 0.965, respectively.[40,41] In the Barnett background samples, the iso- to n-pentane ratio was 0.88 ± 0.8 (linear regression, R^2 = 0.83), suggesting that ONG emissions are dominant in the region.

Regional estimates of HAPs derived from both mobile flux measurements and the CH_4 inventory are summarized in Table 4. With the exception of benzene, MFP-derived rates are approximately 1.5−2.5 times larger than inventory-based values. For the m- and p-isomers of xylene, however, the estimates differ by a factor of 6. The cause of this large discrepancy may be a result of where samples were collected. The highest hexane and m/p-xylene mixing ratios observed during this campaign were downwind of well pads with compressors, where mobile CH_4 leak rates were highest. When compared to the Barnett Shale Special Inventory, developed by the TCEQ for the year 2009, the regional inventory-derived values calculated here are higher. HAP emissions for the 23-county Barnett Shale region

Table 4. Comparison of Regional Fluxes (in kg h^{-1}) for Each of the HAPs Measured Including Hexane, Benzene, Toluene, Ethylbenzene, and the Isomers of Xylene, Derived from MFP Measurements and the Barnett Shale Regional Inventory

	CH_4[28]	C_6H_{14}	'B' C_6H_6	'T' C_7H_8	'E' C_8H_{10}	m/p-'X' C_8H_{10}	o-'X' C_8H_{10}
MFP		1070 ± 340	53 ± 17	257 ± 96	16 ± 5	428 ± 167	33 ± 13
inventory							
low	42,100	642 ± 45	51 ± 4	160 ± 11	8.2 ± 0.6	68 ± 5	11 ± 1
median	48,400	687 ± 49	56 ± 4	171 ± 12	9.0 ± 0.6	72 ± 5	12 ± 1
high	56,400	742 ± 53	60 ± 4	186 ± 13	9.4 ± 0.7	78 ± 6	12 ± 1

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totaled 1,080 tons per year (tpy) or 123 kg h^{-1} for all hazardous compounds (n = 200), compared to over 1,000 kg h^{-1} for the 6 compounds measured in this study.[42] A similar result is observed when quantifying total VOC emissions. The TCEQ Special Inventory estimates emission of 20,800 tpy (2400 kg h^{-1}) for C_3+ alkanes, while another study puts this value at 25,300 tpy (2900 kg h^{-1}).[42,43] Calculation of C_3−C_5 alkane emissions using UCI background corrected canister samples approximates emissions equal to 10,300 kg h^{-1}. One possible explanation for the difference is that a higher proportion of episodic, large emissions was captured by samples in the current study, whereas the previous studies, which rely on self-reporting and averaged monitoring site data, may have missed those emission events.

Comparisons to Other Regions and Implications for Human Health. Whole air samples collected in the Barnett Shale reveal a significant regional source of potentially toxic VOCs from oil and natural gas activities. Mean mixing ratios and emission rate estimates of hexane, benzene, and toluene in the Barnett were similar to values witnessed in ONG producing regions of Colorado and Utah.[40,44] For instance, as part of the 2012−13 Winter Ozone Studies campaign, continuous monitoring of VOCs from a tall tower and tethered balloon revealed emissions of 183 kg h^{-1} of benzene and 228 kg h^{-1} of toluene in the Uintah Basin.[44] The basin, located in northeastern Utah, serves as one of the highest producing oil and gas fields in the US and is home to over 4000 oil and 7000 natural gas wells.[44,45] Despite the smaller number of gas wells compared to the Barnett, the Uintah Basin is also home to active coal mines which potentially contribute to the increased benzene and toluene emissions.[46] In another study conducted in the Houston Ship Channel, VOCs were measured from petrochemical facilities and storage tanks. Average emissions rates of benzene were 460 tons per year, or 53 kg h^{-1}, equivalent to emissions determined in the present study.[47]

The findings presented here suggest a significant regional source of hazardous air pollutants in the Barnett Shale. The potential impacts associated with these emissions are 2-fold: the presence of highly reactive non-methane hydrocarbons could lead to increased surface level ozone (particularly of concern in the DFW NAAQS nonattainment region) and human health impacts associated with exposure to such compounds. The extent to which the emission of these HAPs equates to a larger public health risk is still uncertain though, with some signs suggesting ONG emissions are not of concern for acute health risks. For instance, federal standards regulated by OSHA set 8-h workplace exposure limits of 1 ppm for benzene and 200 ppm for toluene.[48] NIOSH recommended exposure limits are more stringent, at 0.1 ppm for benzene and 100 ppm for toluene.[49] Maximum values observed in the Barnett Shale for these gases were well under these standards, at 4.2 and 17.8 ppb, respectively. However, exemptions to the OSHA standards do exist for crude before it is sent downstream for processing. Some of the highest benzene and toluene mixing ratios in this study were upstream near oil wells, suggesting that workers who manually sample these liquids may be at higher health risk.[49] In addition, a recent study using data from TCEQ monitoring sites throughout the Barnett Shale found that VOC concentrations in the region do not exceed many of the state and federal health regulations and standards.[13] However, it should be noted that the majority of data in that study were from monitoring stations in the dry gas region of the Barnett. As the current work shows, areas with wetter natural gas or conventional oil generate more VOC-enriched emissions.

There is also some evidence to suggest that public concerns for potential chronic health risks are not unwarranted. In the Barnett Shale, the TCEQ sets Effects Screening Levels (ESLs) to regulate ambient levels of benzene considered safe. For long-term exposure concerns, the ESL could be as low as 1.4 ppb, which some oil and gas sites sampled in the current study did exceed.[50] Furthermore, previous studies have shown that even low exposure rates of carcinogens can potentially be harmful to a population. Increased incidence rates and risk of cancer have been observed in communities living downwind of industrial facilities, even with VOC emissions that comply with federal standards.[15,51,52] In Colorado, a study examining birth outcomes and proximity to natural gas development between 1996 and 2009 suggested a link between mothers living within 10 miles of active natural gas wells and occurrence of congenital heart defects and neural tube defects in infants.[53] Overall, more than 80% of peer-review articles published between 2009 and 2015 that discuss unconventional ONG development have indicated public health hazards.[54]

Ultimately, it appears that the type of fossil fuel and where it falls in the supply chain play an important role in overall emissions observed downwind. Processed, distribution-grade natural gas is not a significant source of HAPs or hydrocarbons beyond the light alkanes in the Barnett Shale (Tables 1 and 2). This was also observed in the recent Aliso Canyon natural gas blowout near Los Angeles, CA. The massive leak from an underground gas storage facility was the largest anthropogenic CH_4 point source in the nation, lasting nearly four months and emitting up to 60 metric tonnes of CH_4 per hour.[55] However, because the leak was distribution-grade gas, it did not release a significant amount of aromatic compounds (although the health impacts of exposure to odorants such as methyl mercaptan have yet to be quantified). Emission rates calculated from reported molar emissions ratios correspond to 1.5 ± 0.2 kg h^{-1} of C_6H_6 and 2.2 ± 0.3 kg h^{-1} of C_7H_8. These are much lower than emission rates from oil wells, wet natural gas, and compressor stations presented in the current study.

One aspect not explored in this study, unfortunately, was the difference in emissions during the various stages of a well's lifetime. During well drilling or hydraulic fracturing for instance, VOC emissions may be significant, potentially stemming from fugitive emission, combustion exhaust of drilling rigs, or diesel engines.[2,26,56] Two whole air samples collected at fracking sites were slightly enhanced over background for most VOCs measured but not as high as other ONG sources (Table 1). However, sampling conditions were not ideal (low winds, obstruction from construction walls), and these samples are not considered a good source representation. Flowback operations and well completions were also not targeted for sampling but are believed to increase the risk of health impacts for those working near wells or living in close proximity.[14] Despite the limited number and type of ONG sites samples in this work, measurements do suggest an important local source of these toxic compounds and stress the need for continued measurements from both operators and regulators.

In summary, whole air samples collected in the Barnett Shale revealed an enhancement of numerous hydrocarbons from each of the oil and natural gas sources sampled. Among these enhanced VOCs were potentially toxic compounds including hexane and aromatic compounds, which were 2−50 times greater than the local background on average. Emission

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estimates for these gases suggest a significant regional source, concerning to the large population that lives close to the extensive ONG infrastructure. While it does not appear that emissions caused enhancements that exceed federal workplace guidelines for short-term exposure, benzene enhancements exceeding ESLs highlight the need for continued VOC monitoring, as the potential for human health impacts for long-term exposure exists. More research is needed to address uncertainties in emissions and human exposure, particularly as natural gas production from unconventional sources continues to expand on a global scale.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b02827.

Raw data and Tables S1−S3 (XLSX)

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Notes

The authors declare no competing financial interest.

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Human health risk assessment of air emissions from development of unconventional natural gas resources☆,☆☆

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ABSTRACT

Background: Technological advances (e.g. directional drilling, hydraulic fracturing), have led to increases in unconventional natural gas development (NGD), raising questions about health impacts.
Objectives: We estimated health risks for exposures to air emissions from a NGD project in Garfield County, Colorado with the objective of supporting risk prevention recommendations in a health impact assessment (HIA).
Methods: We used EPA guidance to estimate chronic and subchronic non-cancer hazard indices and cancer risks from exposure to hydrocarbons for two populations: (1) residents living >½ mile from wells and (2) residents living ≤½ mile from wells.
Results: Residents living ≤½ mile from wells are at greater risk for health effects from NGD than are residents living >½ mile from wells. Subchronic exposures to air pollutants during well completion activities present the greatest potential for health effects. The subchronic non-cancer hazard index (HI) of 5 for residents ≤½ mile from wells was driven primarily by exposure to trimethylbenzenes, xylenes, and aliphatic hydrocarbons. Chronic HIs were 1 and 0.4. for residents ≤½ mile from wells and >½ mile from wells, respectively. Cumulative cancer risks were 10 in a million and 6 in a million for residents living ≤½ mile and >½ mile from wells, respectively, with benzene as the major contributor to the risk.
Conclusions: Risk assessment can be used in HIAs to direct health risk prevention strategies. Risk management approaches should focus on reducing exposures to emissions during well completions. These preliminary results indicate that health effects resulting from air emissions during unconventional NGD warrant further study. Prospective studies should focus on health effects associated with air pollution.

1. Introduction

The United States (US) holds large reserves of unconventional natural gas resources in coalbeds, shale, and tight sands. Technological advances, such as directional drilling and hydraulic fracturing, have led to a rapid increase in the development of these resources. For example, shale gas production had an average annual growth rate of 48% over the 2006 to 2010 period and is projected to grow almost fourfold from 2009 to 2035 (US EIA, 2011). The number of unconventional natural gas wells in the US rose from 18,485 in 2004 to 25,145 in 2007 and is expected to continue increasing through at least 2020 (Vidas and Hugman, 2008). With this expansion, it is becoming increasingly common for unconventional natural gas development (NGD) to occur near where people live, work, and play. People living near these development sites are raising public health concerns, as rapid NGD exposes more people to various potential stressors (COGCC, 2009a).

The process of unconventional NGD is typically divided into two phases: well development and production (US EPA, 2010a; US DOE, 2009). Well development involves pad preparation, well drilling, and well completion. The well completion process has three primary stages: 1) completion transitions (concrete well plugs are installed in wells to separate fracturing stages and then drilled out to release gas for production); 2) hydraulic fracturing ("fracking": the high pressure injection of water, chemicals, and propants into the drilled well to release the natural gas); and 3) flowback, the return of fracking and geologic fluids, liquid hydrocarbons ("condensate") and natural gas to the surface (US EPA, 2010a; US DOE, 2009). Once development is

Abbreviations: BTEX, benzene, toluene, ethylbenzene, and xylenes; COGCC, Colorardo Oil and Gas Conservation Commission; HAP, hazardous air pollutant; HI, hazard index; HIA, health impact assessment; HQ, hazard quotient; NATA, National Air Toxics Assessment; NGD, natural gas development.

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complete, the “salable” gas is collected, processed, and distributed. While methane is the primary constituent of natural gas, it contains many other chemicals, including alkanes, benzene, and other aromatic hydrocarbons (TERC, 2009).

As shown by ambient air studies in Colorado, Texas, and Wyoming, the NGD process results in direct and fugitive air emissions of a complex mixture of pollutants from the natural gas resource itself as well as diesel engines, tanks containing produced water, and on site materials used in production, such as drilling muds and fracking fluids (CDPHE, 2009; Frazier, 2009; Walther, 2011; Zielinska et al., 2011). The specific contribution of each of these potential NGD sources has yet to be ascertained and pollutants such as petroleum hydrocarbons are likely to be emitted from several of these NGD sources. This complex mixture of chemicals and resultant secondary air pollutants, such as ozone, can be transported to nearby residences and population centers (Walther, 2011; GCPH, 2010).

Multiple studies on inhalation exposure to petroleum hydrocarbons in occupational settings as well as residences near refineries, oil spills and petrol stations indicate an increased risk of eye irritation and headaches, asthma symptoms, acute childhood leukemia, acute myelogenous leukemia, and multiple myeloma (Glass et al., 2003; Kirkeleit et al., 2008; Brosselin et al., 2009; Kim et al., 2009; White et al., 2009). Many of the petroleum hydrocarbons observed in these studies are present in and around NGD sites (TERC, 2009). Some, such as benzene, ethylbenzene, toluene, and xylene (BTEX) have robust exposure and toxicity knowledge bases, while toxicity information for others, such as heptane, octane, and diethylbenzene, is more limited. Assessments in Colorado have concluded that ambient benzene levels demonstrate an increased potential risk of developing cancer as well as chronic and acute noncancer health effects in areas of Garfield County Colorado where NGD is the only major industry other than agriculture (CDPHE, 2007; Coons and Walker, 2008; CDPHE, 2010). Health effects associated with benzene include acute and chronic nonlymphocytic leukemia, acute myeloid leukemia, chronic lymphocytic leukemia, anemia, and other blood disorders and immunological effects. (ATSDR, 2007a, IRIS, 2011). In addition, maternal exposure to ambient levels of benzene recently has been associated with an increase in birth prevalence of neural tube defects (Lupo et al., 2011). Health effects of xylene exposure include eye, nose, and throat irritation, difficulty in breathing, impaired lung function, and nervous system impairment (ATSDR, 2007b). In addition, inhalation of xylenes, benzene, and alkanes can adversely affect the nervous system (Carpenter et al., 1978; Nilsen et al., 1988; Galvin and Marashi, 1999; ATSDR, 2007a; ATSDR, 2007b).

Previous assessments are limited in that they were not able to distinguish between risks from ambient air pollution and specific NGD stages, such as well completions or risks between residents living near wells and residents living further from wells. We were able to isolate risks to residents living near wells during the flowback stage of well completions by using air quality data collected at the perimeter of the wells while flowback was occurring.

Battlement Mesa (population ~5000) located in rural Garfield County, Colorado is one community experiencing the rapid expansion of NGD in an unconventional tight sand resource. A NGD operator has proposed developing 200 gas wells on 9 well pads located as close as 500 ft from residences. Colorado Oil and Gas Commission (COGCC) rules allow natural gas wells to be placed as close as 150 ft from residences (COGCC, 2009b). Because of community concerns, as described elsewhere, we conducted a health impact assessment (HIA) to assess how the project may impact public health (Witter et al., 2011), working with a range of stakeholders to identify the potential public health risks and benefits.

In this article, we illustrate how a risk assessment was used to support elements of the HIA process and inform risk prevention recommendations by estimating chronic and subchronic non-cancer hazard indices (HIs) and lifetime excess cancer risks due to NGD air emissions.

2. Methods

We used standard United States Environmental Protection Agency (EPA) methodology to estimate non-cancer HIs and excess lifetime cancer risks for exposures to hydrocarbons (US EPA, 1989; US EPA, 2004) using residential exposure scenarios developed for the NGD project. We used air toxics data collected in Garfield County from January 2008 to November 2010 as part of a special study of short term exposures as well as on-going ambient air monitoring program data to estimate subchronic and chronic exposures and health risks (Frazier, 2009; GCPH, 2009; GCPH, 2010; GCPH, 2011; Antero, 2010).

2.1. Sample collection and analysis

All samples were collected and analyzed according to published EPA methods. Analyses were conducted by EPA certified laboratories. The Garfield County Department of Public Health (GCPH) and Olsson Associates, Inc. (Olsson) collected ambient air samples into evacuated SUMMA® passivated stainless-steel canisters over 24-hour intervals. The GCPH collected the samples from a fixed monitoring station and along the perimeters of four well pads and shipped samples to Eastern Research Group for analysis of 78 hydrocarbons using EPA's compendium method TO-12, Method for the Determination of Non-Methane Organic Compounds in Ambient Air Using Cyrogenic Preconcentration and Direct Flame Ionization Detection (US EPA, 1999). Olsson collected samples along the perimeter of one well pad and shipped samples to Atmospheric Analysis and Consulting, Inc. for analysis of 56 hydrocarbons (a subset of the 78 hydrocarbons determined by Eastern Research Group) using method TO-12. Per method TO-12, a fixed volume of sample was cryogenically concentrated and then desorbed onto a gas chromatography column equipped with a flame ionization detector. Chemicals were identified by retention time and reported in a concentration of parts per billion carbon (ppbC). The ppbC values were converted to micrograms per cubic meter ($\mu g/m^3$) at 01.325 kPa and 298.15 K.

Two different sets of samples were collected from rural (population < 50,000) areas in western Garfield County over varying time periods. The main economy, aside from the NGD industry, of western Garfield County is agricultural. There is no other major industry.

2.1.1. NGD area samples

The GCPH collected ambient air samples every six days between January 2008 and November 2010 (163 samples) from a fixed monitoring station located in the midst of rural home sites and ranches and NGD, during both well development and production. The site is located on top of a small hill and 4 miles upwind of other potential emission sources, such as a major highway (Interstate-70) and the town of Silt, CO (GCPH, 2009; GCPH, 2010; GCPH, 2011).

2.1.2. Well completion samples

The GCPH collected 16 ambient air samples at each cardinal direction along 4 well pad perimeters (130 to 500 ft from the well pad center) in rural Garfield County during well completion activities. The samples were collected on the perimeter of 4 well pads being developed by 4 different natural gas operators in summer 2008 (Frazier, 2009). The GCPH worked closely with the NGD operators to ensure these air samples were collected during the period while at least one well was on uncontrolled (emissions not controlled) flowback into collection tanks vented directly to the air. The number of wells on each pad and other activities occurring on the pad were not documented. Samples were collected over 24 to 27-hour intervals, and samples included emissions from both uncontrolled flowback and diesel engines (i.e., from. trucks and generators supporting completion activities). In addition, the GCPH collected a background sample 0.33 to 1 mile from each well pad (Frazier, 2009). The highest hydrocarbon levels corresponded to samples collected directly downwind of the tanks (Frazier, 2009; Antero, 2010). The lowest hydrocarbon levels corresponded either to background samples or samples collected upwind of the flowback tanks (Frazier, 2009; Antero, 2010).

Antero Resources Inc., a natural gas operator, contracted Olsson to collect eight 24-hour integrated ambient air samples at each cardinal direction at 350 and 500 ft from the well pad center during well completion activities conducted on one of their well pads in summer 2010 (Antero, 2010). Of the 12 wells on this pad, 8 were producing salable natural gas; 1 had been drilled but not completed; 2 were being hydraulically fractured during daytime hours, with ensuing uncontrolled flowback during nighttime hours; and 1 was on uncontrolled flowback during nighttime hours.

All five well pads are located in areas with active gas production, approximately 1 mile from Interstate-70.

2.2. Data assessment

We evaluated outliers and compared distributions of chemical concentrations from NGD area and well completion samples using Q–Q plots and the Mann–Whitney *U* test, respectively, in EPA's ProUCL version 4.00.05 software (US EPA, 2010b). The Mann–Whitney *U* test was used because the measurement data were not normally distributed. Distributions were considered as significantly different at an alpha of 0.05. Per EPA guidance, we assigned the exposure concentration as either the 95% upper confidence limit (UCL) of the mean concentration for compounds found in 10 or more samples or the maximum detected concentration for compounds found in more than 1 but fewer than 10 samples. This latter category included three compounds: 1,3-butadiene, 2,2,4-trimethylpentane, and styrene in the well completion samples. EPA's ProUCL software was used to select appropriate methods based on sample distributions and detection frequency for computing 95% UCLs of the mean concentration (US EPA, 2010b).

2.3. Exposure assessment

Risks were estimated for two populations: (1) residents >½ mile from wells; and (2) residents ≤½ mile from wells. We defined residents ≤½ mile from wells as living near wells, based on residents reporting odor complaints attributed to gas wells in the summer of 2010 (COGCC, 2011).

Exposure scenarios were developed for chronic non-cancer HIs and cancer risks. For both populations, we assumed a 30-year project duration based on an estimated 5-year well development period for all well pads, followed by 20 to 30 years of production. We assumed a resident lives, works, and otherwise remains within the town 24 h/day, 350 days/year and that lifetime of a resident is 70 years, based on standard EPA reasonable maximum exposure (RME) defaults (US EPA, 1989).

2.3.1. Residents >½ mile from well pads

As illustrated in Fig. 1, data from the NGD area samples were used to estimate chronic and subchronic risks for residents >½ mile from well development and production throughout the project. The exposure concentrations for this population were the 95% UCL on the mean concentration and median concentration from the 163 NGD samples.

2.3.2. Residents ≤½ mile from well pads

To evaluate subchronic non-cancer HIs from well completion emissions, we estimated that a resident lives ≤½ mile from two well pads resulting a 20-month exposure duration based on 2 weeks per well for completion and 20 wells per pad, assuming some overlap in between activities. The subchronic exposure concentrations for this population were the 95% UCL on the mean concentration and the median concentration from the 24 well completion samples. To evaluate chronic risks to residents ≤½ mile from wells throughout the NGD project, we calculated a time-weighted exposure concentration (C_{S+c}) to account for exposure to emissions from well completions for 20-months followed by 340 months of exposure to emissions from the NGD area using the following formula:

$$C_{S+c} = (C_c \times ED_c/ED) + (C_S \times ED_S/ED)$$

where:

C_c Chronic exposure point concentration (μg/m^3) based on the 95% UCL of the mean concentration or median concentration from the 163 NGD area samples

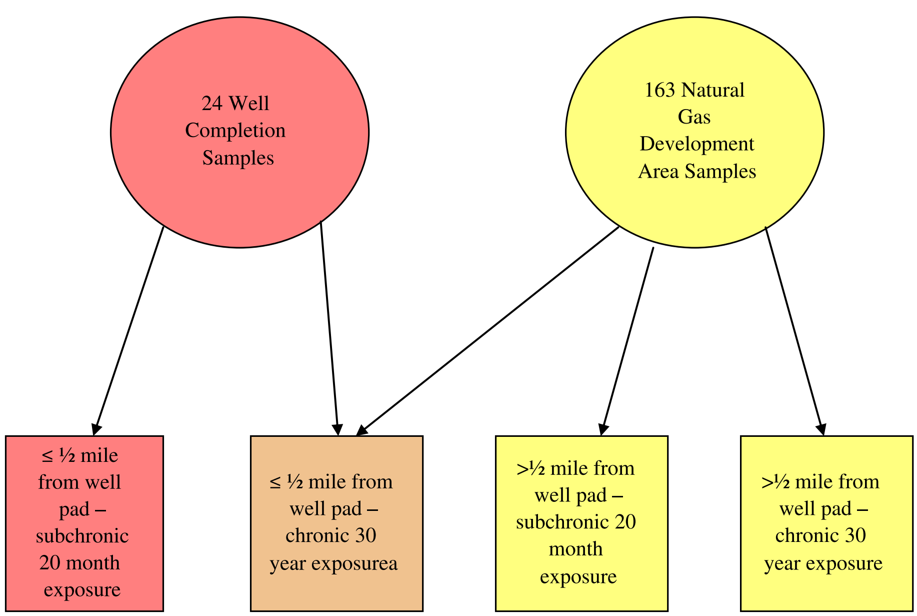

Fig. 1. Relationship between completion samples and natural gas development area samples and residents living ≤½ mile and >½ mile from wells. [a]Time weighted average based on 20-month contribution from well completion samples and 340-month contribution from natural gas development samples.

ED_c Chronic exposure duration
C_S Subchronic exposure point concentration (μg/m^3) based on the 95% UCL of the mean concentration or median concentration from the 24 well completion samples
ED_S Subchronic exposure duration
ED Total exposure duration

2.4. Toxicity assessment and risk characterization

For non-carcinogens, we expressed inhalation toxicity measurements as a reference concentration (RfC in units of μg/m^3 air). We used chronic RfCs to evaluate long-term exposures of 30 years and subchronic RfCs to evaluate subchronic exposures of 20-months. If a subchronic RfC was not available, we used the chronic RfC. We obtained RfCs from (in order of preference) EPA's Integrated Risk Information System (IRIS) (US EPA, 2011), California Environmental Protection Agency (CalEPA) (CalEPA, 2003), EPA's Provisional Peer-Reviewed Toxicity Values (ORNL, 2009), and Health Effects Assessment Summary Tables (US EPA, 1997). We used surrogate RfCs according to EPA guidance for C_5 to C_{18} aliphatic and C_6 to C_{18} aromatic hydrocarbons which did not have a chemical-specific toxicity value (US EPA, 2009a). We derived semi-quantitative hazards, in terms of the hazard quotient (HQ), defined as the ratio between an estimated exposure concentration and RfC. We summed HQs for individual compounds to estimate the total cumulative HI. We then separated HQs specific to neurological, respiratory, hematological, and developmental effects and calculated a cumulative HI for each of these specific effects.

For carcinogens, we expressed inhalation toxicity measurements as inhalation unit risk (IUR) in units of risk per μg/m^3. We used IURs from EPA's IRIS (US EPA, 2011) when available or the CalEPA (CalEPA, 2003). The lifetime cancer risk for each compound was derived by multiplying estimated exposure concentration by the IUR. We summed cancer risks for individual compounds to estimate the cumulative cancer risk. Risks are expressed as excess cancers per 1 million population based on exposure over 30 years.

Toxicity values (i.e., RfCs or IURs) or a surrogate toxicity value were available for 45 out of 78 hydrocarbons measured. We performed a quantitative risk assessment for these hydrocarbons. The remaining 33 hydrocarbons were considered qualitatively in the risk assessment.

3. Results

3.1. Data assessment

Evaluation of potential outliers revealed no sampling, analytical, or other anomalies were associated with the outliers. In addition, removal of potential outliers from the NGD area samples did not change the final HIs and cancer risks. Potential outliers in the well completion samples were associated with samples collected downwind from flowback tanks and are representative of emissions during flowback. Therefore, no data was removed from either data set.

Descriptive statistics for concentrations of the hydrocarbons used in the quantitative risk assessment are presented in Table 1. A list of the hydrocarbons detected in the samples that were considered qualitatively in the risk assessment because toxicity values were not available is presented in Table 2. Descriptive statistics for all hydrocarbons are available in Supplemental Table 1. Two thirds more hydrocarbons were detected at a frequency of 100% in the well completion samples (38 hydrocarbons) than in the NGD area samples (23 hydrocarbons). Generally, the highest alkane and aromatic hydrocarbon median concentrations were observed in the well completion samples, while the highest median concentrations of several alkenes were observed in the NGD area samples. Median concentrations of benzene, ethylbenzene, toluene, and m-xylene/p-xlyene were 2.7, 4.5, 4.3, and 9 times higher in the well completion samples than in the NGD area samples, respectively. Wilcoxon–Mann–Whitney test results indicate that

Table 1
Descriptive statistics for hydrocarbon concentrations with toxicity values in 24-hour integrated samples collected in NGD area and samples collected during well completions.

Hydrocarbon (μg/m^3)	NGD area sample results[a]							Well completion sample results[b]						
	No.	% > MDL	Med	SD	95% UCL[c]	Min	Max	No.	% > MDL	Med	SD	95% UCL[c]	Min	Max
1,2,3-Trimethylbenzene	163	39	0.11	0.095	0.099	0.022	0.85	24	83	0.84	2.3	3.2	0.055	12
1,2,4-Trimethylbenzene	163	96	0.18	0.34	0.31	0.063	3.1	24	100	1.7	17	21	0.44	83
1,3,5-Trimethylbenzene	163	83	0.12	0.13	0.175	0.024	1.2	24	100	1.3	16	19.5	0.33	78
1,3-Butadiene	163	7	0.11	0.020	0.0465	0.025	0.15	16	56	0.11	0.021	NC	0.068	0.17
Benzene	163	100	0.95	1.3	1.7	0.096	14	24	100	2.6	14	20	0.94	69
Cyclohexane	163	100	2.1	8.3	6.2	0.11	105	24	100	5.3	43	58	2.21	200
Ethylbenzene	163	95	0.17	0.73	0.415	0.056	8.1	24	100	0.77	47	54	0.25	230
Isopropylbenzene	163	38	0.15	0.053	0.074	0.020	0.33	24	67	0.33	1.0	1.0	0.0	4.8
Methylcyclohexane	163	100	3.7	4.0	6.3	0.15	24	24	100	14	149	190	3.1	720
m-Xylene/p-Xylene	163	100	0.87	1.2	1.3	0.16	9.9	24	100	7.8	194	240	2.0	880
n-Hexane	163	100	4.0	4.2	6.7	0.13	25	24	100	7.7	57	80	1.7	255
n-Nonane	163	99	0.44	0.49	0.66	0.064	3.1	24	100	3.6	61	76	1.2	300
n-Pentane	163	100	9.1	9.8	14	0.23	62	24	100	11	156	210	3.9	550
n-Propylbenzene	163	66	0.10	0.068	0.10	0.032	0.71	24	88	0.64	2.4	3.3	0.098	12
o-Xylene	163	97	0.22	0.33	0.33	0.064	3.6	24	100	1.2	40	48.5	0.38	190
Propylene	163	100	0.34	0.23	0.40	0.11	2.5	24	100	0.41	0.34	0.60	0.16	1.9
Styrene	163	15	0.15	0.26	0.13	0.017	3.4	24	21	0.13	1.2	NC	0.23	5.9
Toluene	163	100	1.8	6.2	4.8	0.11	79	24	100	7.8	67	92	2.7	320
Aliphatic hydrocarbons C_5–C_8[d]	163	NC	29	NA	44	1.7	220	24	NC	56	NA	780	24	2700
Aliphatic hydrocarbons C_9–C_{18}[e]	163	NC	1.3	NA	14	0.18	400	24	NC	7.9	NA	100	1.4	390
Aromatic hydrocarbons C_9–C_{18}[f]	163	NC	0.57	NA	0.695	0.17	5.6	24	NC	3.7	NA	27	0.71	120

Abbreviations: Max, maximum detected concentration; Med, median; Min, minimum detected concentration; NGD, natural gas development; NC, not calculated; No., number of samples; SD, standard deviation; % > MDL, percent greater than method detection limit; μg/m^3 micrograms per cubic meter; 95% UCL 95% upper confidence limit on the mean.

[a] Samples collected at one site every 6 six days between 2008 and 2010.

[b] Samples collected at four separate sites in summer 2008 and one site in summer 2010.

[c] Calculated using EPA's ProUCL version 4.00.05 software (US EPA, 2010b).

[d] Sum of 2,2,2-trimethylpentane, 2,2,4-trimethylpentane, 2,2-dimethylbutane, 2,3,4-trimethylpentane, 2,3-dimethylbutane, 2,3-dimethylpentane, 2,4-dimethylpentane, 2-methylheptane, 2-methylhexane, 2-methylpentane, 3-methylheptane, 3-methylhexane, 3-methylpentane, cyclopentane, isopentane, methylcyclopentane, n-heptane, n-octane.

[e] Sum of n-decane, n-dodecane, n-tridecane, n-undecane.

[f] Sum of m-diethylbenzene, m-ethyltoluene, o-ethyltoluene, p-diethylbenzene, p-ethyltoluene.

Table 2
Detection frequencies of hydrocarbons without toxicity values detected in NGD area or well completion samples.

Hydrocarbon	NGD area sample[a] detection frequency (%)	Well completion sample[b] detection frequency (%)
1-Dodecene	36	81
1-Heptene	94	100
1-Hexene	63	79
1-Nonene	52	94
1-Octene	29	75
1-Pentene	98	79
1-Tridecene	7	38
1-Undecene	28	81
2-Ethyl-1-butene	1	0
2-Methyl-1-butene	29	44
2-Methyl-1-pentene	1	6
2-Methyl-2-butene	36	69
3-Methyl-1-butene	6	6
4-Methyl-1-pentene	16	69
Acetylene	100	92
a-Pinene	63	100
b-Pinene	10	44
cis-2-Butene	58	75
cis-2-Hexene	13	81
cis-2-Pentene	38	54
Cyclopentene	44	94
Ethane	100	100
Ethylene	100	100
Isobutane	100	100
Isobutene/1-Butene	73	44
Isoprene	71	96
n-Butane	98	100
Propane	100	100
Propyne	1	0
trans-2-Butene	80	75
trans-2-Hexene	1	6
trans-2-Pentene	55	83

Abbreviations: NGD, natural gas development.
[a] Samples collected at one site every 6 six days between 2008 and 2010.
[b] Samples collected at four separate sites in summer 2008 and one site in summer 2010.

concentrations of hydrocarbons from well completion samples were significantly higher than concentrations from NGD area samples ($p<0.05$) with the exception of 1,2,3-trimethylbenzene, n-pentane, 1,3-butadiene, isopropylbenzene, n-propylbenzene, propylene, and styrene (Supplemental Table 2).

3.2. Non-cancer hazard indices

Table 3 presents chronic and subchronic RfCs used in calculating non-cancer HIs, as well critical effects and other effects. Chronic non-cancer HQ and HI estimates based on ambient air concentrations are presented in Table 4. The total chronic HIs based on the 95% UCL of the mean concentration were 0.4 for residents >½ mile from wells and 1 for residents ≤½ mile from wells. Most of the chronic non-cancer hazard is attributed to neurological effects with neurological HIs of 0.3 for residents >½ mile from wells and 0.9 for residents ≤½ mile from wells.

Total subchronic non-cancer HQs and HI estimates are presented in Table 5. The total subchronic HIs based on the 95% UCL of the mean concentration were 0.2 for residents >½ mile from wells and 5 for residents ≤½ mile from wells. The subchronic non-cancer hazard for residents >½ mile from wells is attributed mostly to respiratory effects (HI = 0.2), while the subchronic hazard for residents ≤½ mile from wells is attributed to neurological (HI = 4), respiratory (HI = 2), hematologic (HI = 3), and developmental (HI = 1) effects.

For residents >½ mile from wells, aliphatic hydrocarbons (51%), trimethylbenzenes (22%), and benzene (14%) are primary contributors to the chronic non-cancer HI. For residents ≤½ mile from wells, trimethylbenzenes (45%), aliphatic hydrocarbons (32%), and xylenes (17%) are primary contributors to the chronic non-cancer HI, and trimethylbenzenes (46%), aliphatic hydrocarbons (21%) and xylenes (15%) also are primary contributors to the subchronic HI.

3.3. Cancer risks

Cancer risk estimates calculated based on measured ambient air concentrations are presented in Table 6. The cumulative cancer risks based on the 95% UCL of the mean concentration were 6 in a million for residents >½ from wells and 10 in a million for residents ≤½ mile from wells. Benzene (84%) and 1,3-butadiene (9%) were the primary contributors to cumulative cancer risk for residents >½ mile from wells. Benzene (67%) and ethylbenzene (27%) were the primary contributors to cumulative cancer risk for residents ≤½ mile from wells.

4. Discussion

Our results show that the non-cancer HI from air emissions due to natural gas development is greater for residents living closer to wells. Our greatest HI corresponds to the relatively short-term (i.e., subchronic), but high emission, well completion period. This HI is driven principally by exposure to trimethylbenzenes, aliphatic hydrocarbons, and xylenes, all of which have neurological and/or respiratory effects. We also calculated higher cancer risks for residents living nearer to wells as compared to residents residing further from wells. Benzene is the major contributor to lifetime excess cancer risk for both scenarios. It also is notable that these increased risk metrics are seen in an air shed that has elevated ambient levels of several measured air toxics, such as benzene (CDPHE, 2009; GCPH, 2010).

4.1. Representation of exposures from NGD

It is likely that NGD is the major source of the hydrocarbons observed in the NGD area samples used in this risk assessment. The NGD area monitoring site is located in the midst of multi-acre rural home sites and ranches. Natural gas is the only industry in the area other than agriculture. Furthermore, the site is at least 4 miles upwind from any other major emission source, including Interstate 70 and the town of Silt, Colorado. Interestingly, levels of benzene, m,p-xylene, and 1,3,5-trimethylbenzene measured at this rural monitoring site in 2009 were higher than levels measured at 27 out of 37 EPA air toxics monitoring sites where SNMOCs were measured, including urban sites such as Elizabeth, NJ, Dearborn, MI, and Tulsa, OK (GCPH, 2010; US EPA, 2009b). In addition, the 2007 Garfield County emission inventory attributes the bulk of benzene, xylene, toluene, and ethylbenzene emissions in the county to NGD, with NGD point and non-point sources contributing five times more benzene than any other emission source, including on-road vehicles, wildfires, and wood burning. The emission inventory also indicates that NGD sources (e.g. condensate tanks, drill rigs, venting during completions, fugitive emissions from wells and pipes, and compressor engines) contributed ten times more VOC emissions than any source, other than biogenic sources (e.g. plants, animals, marshes, and the earth) (CDPHE, 2009).

Emissions from flowback operations, which may include emissions from various sources on the pads such as wells and diesel engines, are likely the major source of the hydrocarbons observed in the well completion samples. These samples were collected very near (130 to 500 ft from the center) well pads during uncontrolled flowback into tanks venting directly to the air. As for the NGD area samples, no sources other than those associated with NGD were in the vicinity of the sampling locations.

Subchronic health effects, such as headaches and throat and eye irritation reported by residents during well completion activities

Table 3
Chronic and subchronic reference concentrations, critical effects, and major effects for hydrocarbons in quantitative risk assessment.

Hydrocarbon	Chronic		Subchronic		Critical effect/ target organ	Other effects
	RfC ($\mu g/m^3$)	Source	RfC ($\mu g/m^3$)	Source		
1,2,3-Trimethylbenzene	5.00E+00	PPTRV	5.00E+01	PPTRV	Neurological	Respiratory, hematological
1,3,5-Trimethylbenzene	6.00E+00	PPTRV	1.00E+01	PPTRV	Neurological	Hematological
Isopropylbenzene	4.00E+02	IRIS	9.00E+01	HEAST	Renal	Neurological, respiratory
n-Hexane	7.00E+02	IRIS	2.00E+03	PPTRV	Neurological	–
n-Nonane	2.00E+02	PPTRV	2.00E+03	PPTRV	Neurological	Respiratory
n-Pentane	1.00E+03	PPTRV	1.00E+04	PPTRV	Neurological	–
Styrene	1.00E+03	IRIS	3.00E+03	HEAST	Neurological	–
Toluene	5.00E+03	IRIS	5.00E+03	PPTRV	Neurological	Developmental, respiratory
Xylenes, total	1.00E+02	IRIS	4.00E+02	PPTRV	Neurological	Developmental, respiratory
n-propylbenzene	1.00E+03	PPTRV	1.00E+03	Chronic RfC PPTRV	Developmental	Neurological
1,2,4-Trimethylbenzene	7.00E+00	PPTRV	7.00E+01	PPTRV	Decrease in blood clotting time	Neurological, respiratory
1,3-Butadiene	2.00E+00	IRIS	2.00E+00	Chronic RfC IRIS	Reproductive	Neurological, respiratory
Propylene	3.00E+03	CalEPA	1.00E+03	Chronic RfC CalEPA	Respiratory	–
Benzene	3.00E+01	ATSDR	8.00E+01	PPTRV	Decreased lymphocyte count	Neurological, developmental, reproductive
Ethylbenzene	1.00E+03	ATSDR	9.00E+03	PPTRV	Auditory	Neurological, respiratory, renal
Cyclohexane	6.00E+03	IRIS	1.80E+04	PPTRV	Developmental	Neurological
Methylcyclohexane	3.00E+03	HEAST	3.00E+03	HEAST	Renal	–
Aliphatic hydrocarbons C_5–C_8[a]	6E+02	PPTRV	2.7E+04	PPTRV	Neurological	–
Aliphatic hydrocarbons C_9–C_{18}	1E+02	PPTRV	1E+02	PPTRV	Respiratory	–
Aromatic hydrocarbons C_9–C_{18}[b]	1E+02	PPTRV	1E+03	PPRTV	Decreased maternal body weight	Respiratory

Abbreviations: 95%UCL, 95% upper confidence limit; CalEPA, California Environmental Protection Agency; HEAST, EPA Health Effects Assessment Summary Tables 1997; HQ, hazard quotient; IRIS, Integrated Risk Information System; Max, maximum; PPTRV, EPA Provisional Peer-Reviewed Toxicity Value; RfC, reference concentration; $\mu g/m^3$, micrograms per cubic meter. Data from CalEPA 2011; IRIS (US EPA, 2011); ORNL 2011.
[a] Based on PPTRV for commercial hexane.
[b] Based on PPTRV for high flash naphtha.

occurring in Garfield County, are consistent with known health effects of many of the hydrocarbons evaluated in this analysis (COGCC, 2011; Witter et al., 2011). Inhalation of trimethylbenzenes and xylenes can irritate the respiratory system and mucous membranes with effects ranging from eye, nose, and throat irritation to difficulty in breathing and impaired lung function (ATSDR, 2007a;

Table 4
Chronic hazard quotients and hazard indices for residents living >½ mile from wells and residents living ≤½ mile from wells.

Hydrocarbon	>½ mile		≤½ mile	
	Chronic HQ based on median concentration	Chronic HQ based on 95% UCL of mean concentration	Chronic HQ based on median concentration	Chronic HQ based on 95% UCL of mean concentration
1,2,3-Trimethylbenzene	2.09E−02	1.90E−02	2.87E−02	5.21E−02
1,2,4-Trimethylbenzene	2.51E−02	4.22E−02	3.64E−02	2.01E−01
1,3,5-Trimethylbenzene	1.96E−02	2.80E−02	3.00E−02	1.99E−01
1,3-Butadiene	5.05E−02	2.23E−02	5.05E−02	2.25E−02
Benzene	3.03E−02	5.40E−02	3.32E−02	8.70E−02
Cyclohexane	3.40E−04	9.98E−04	3.67E−04	1.46E−03
Ethylbenzene	1.63E−04	3.98E−04	1.95E−04	3.23E−03
Isopropylbenzene	3.68E−04	1.78E−04	3.90E−04	3.05E−04
Methylcyclohexane	1.18E−03	2.00E−03	1.36E−03	5.32E−03
n-Hexane	5.49E−03	9.23E−03	5.76E−03	1.47E−02
n-Nonane	2.11E−03	3.14E−03	2.95E−03	2.31E−02
n-Pentane	8.71E−03	1.32E−02	8.79E−03	2.39E−02
n-propylbenzene	9.95E−05	9.59E−05	1.28E−04	2.64E−04
Propylene	1.09E−04	1.27E−04	1.10E−04	1.30E−04
Styrene	1.43E−04	1.25E−04	1.42E−04	4.32E−04
Toluene	3.40E−04	9.28E−04	4.06E−04	1.86E−03
Xylenes, total	1.16E−02	1.57E−02	1.54E−02	1.71E−01
Aliphatic hydrocarbons C_5–C_8	4.63E−02	7.02E−02	4.87E−02	1.36E−01
Aliphatic hydrocarbons C_9–C_{18}	1.22E−02	1.35E−01	1.58E−02	1.83E−01
Aromatic hydrocarbons C_9–C_{18}	5.44E−03	6.67E−03	7.12E−03	2.04E−02
Total Hazard Index	2E−01	4E−01	3E−01	1E+00
Neuorological Effects Hazard Index[a]	2E−01	3E−01	3E−01	9E−01
Respiratory Effects Hazard Index[b]	1E−01	2E−02	2E−02	7E−01
Hematogical Effects Hazard Index[c]	1E−01	1E−01	1E−01	5E−01
Developmental Effects Hazard Index[d]	4E−02	7E−02	5E−02	3E−01

Abbreviations: 95%UCL, 95% upper confidence limit; HQ, hazard quotient.
[a] Sum of HQs for hydrocarbons with neurological effects: 1,2,3-Trimethylbenzene, 1,2,4-Trimethylbenzene, 1,3,5-Trimethylbenzene, 1,3-butadiene, benzene, cyclohexane, ethylbenzene, isopropylbenzene, n-hexane, n-nonane, n-pentane, n-propylbenzene, styrene, toluene, xylenes, aliphatic C_5–C_8 hydrocarbons.
[b] Sum of HQs for hydrocarbons with respiratory effects: 1,2,3-Trimethylbenzene, 1,2,4-Trimethylbenzene, 1,3-butadiene, ethylbenzene, isopropylbenzene, n-nonane, propylene, toluene, xylenes, aliphatic C_9–C_{18} hydrocarbons, aromatic C_9–C_{18} hydrocarbons.
[c] Sum of HQs for hydrocarbons with hematological effects: 1,2,3-trimethylbenzene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, benzene.
[d] Sum of HQs for hydrocarbons with developmental effects: benzene, cyclohexane, toluene, and xylenes.

Table 5
Subchronic hazard quotients and hazard indices residents living >½ mile from wells and residents living ≤½ mile from wells.

Hydrocarbon (μg/m^3)	>½ mile		≤½ mile	
	Subchronic HQ based on median concentration	Subchronic HQ based on 95% UCL of mean concentration	Subchronic HQ based on median concentration	Subchronic HQ based on 95% UCL of mean concentration
1,2,3-Trimethylbenzene	2.09E−03	1.90E−03	1.67E−02	6.40E−02
1,2,4-Trimethylbenzene	2.51E−03	4.22E−03	2.38E−02	3.02E−01
1,3,5-Trimethylbenzene	1.18E−02	1.68E−02	1.29E−01	1.95E+00
1,3-Butadiene	5.04E−02	2.23E−02	5.25E−02	8.30E−02
Benzene	1.14E−02	2.02E−02	3.25E−02	2.55E−01
Cyclohexane	1.13E−04	3.33E−04	2.93E−04	3.24E−03
Ethylbenzene	1.81E−05	4.42E−05	8.56E−05	5.96E−03
Isopropylbenzene	1.63E−03	7.92E−04	3.62E−03	1.14E−02
Methylcyclohexane	1.18E−03	2.01E−03	4.67E−03	6.47E−02
n-Hexane	1.92E−03	3.23E−03	3.86E−03	3.98E−02
n-Nonane	2.11E−04	3.14E−04	1.80E−03	3.78E−02
n-Pentane	8.71E−04	1.32E−03	1.05E−03	2.13E−02
n-propylbenzene	9.95E−05	9.57E−05	6.36E−04	3.26E−03
Propylene	1.43E−04	3.80E−04	4.12E−04	6.02E−04
Styrene	5.68E−04	4.16E−05	4.00E−06	1.97E−03
Toluene	4.18E−05	9.28E−04	2.46E−04	1.84E−02
Xylenes, total	2.91E−03	3.93E−03	2.05E−02	7.21E−01
Aliphatic hydrocarbons C_5–C_8	1.07E−03	1.63E−03	2.07E−03	2.89E−02
Aliphatic hydrocarbons C_9–C_{18}	1.3E−02	1.41E−01	7.9E−02	1.03E−00
Aromatic hydrocarbons C_9–C_{18}	6.00E−04	6.95E−04	3.7E−03	2.64E−02
Total Hazard Index	1E−01	2E−01	4E−01	5E+00
Neurological Effects Hazard Index[a]	9E−02	8E−02	3E−01	4E+00
Respiratory Effects Hazard Index[b]	7E−02	2E−01	2E−01	2E+00
Hematogical Effects Hazard Index[c]	3E−02	4E−02	2E−01	3E+00
Developmental Effects Hazard Index[d]	1E−02	3E−02	5E−02	1E+00

Abbreviations: 95%UCL, 95% upper confidence limit; HQ, hazard quotient.
[a] Sum of HQs for hydrocarbons with neurological effects: 1,2,3-Trimethylbenzene, 1,2,4-Trimethylbenzene, 1,3,5-Trimethylbenzene, 1,3-butadiene, benzene, cyclohexane, ethylbenzene, isopropylbenzene, n-hexane, n-nonane, n-pentane, n-propylbenzene, styrene, toluene, xylenes, aliphatic C_5–C_8 hydrocarbons.
[b] Sum of HQs for hydrocarbons with respiratory effects: 1,2,3-Trimethylbenzene, 1,2,4-Trimethylbenzene, 1,3-butadiene, ethylbenzene, isopropylbenzene, n-nonane, propylene, toluene, xylenes, aliphatic C_9–C_{18} hydrocarbons, aromatic C_9–C_{18} hydrocarbons.
[c] Sum of HQs for hydrocarbons with hematological effects: 1,2,3-trimethylbenzene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, benzene.
[d] Sum of HQs for hydrocarbons with developmental effects: benzene, cyclohexane, toluene, and xylenes.

ATSDR, 2007b; US EPA, 1994). Inhalation of trimethylbenzenes, xylenes, benzene, and alkanes can adversely affect the nervous system with effects ranging from dizziness, headaches, fatigue at lower exposures to numbness in the limbs, incoordination, tremors, temporary limb paralysis, and unconsciousness at higher exposures (Carpenter et al., 1978; Nilsen et al., 1988; US EPA, 1994; Galvin and Marashi, 1999; ATSDR, 2007a; ATSDR, 2007b).

4.2. Risk assessment as a tool for health impact assessment

HIA is a policy tool used internationally that is being increasingly used in the United States to assess multiple complex hazards and exposures in communities. Comparison of risks between residents based on proximity to wells illustrates how the risk assessment process can be used to support the HIA process. An important component of the HIA process is to identify where and when public health is most likely to be impacted and to recommend mitigations to reduce or eliminate the potential impact (Collins and Koplan, 2009). This risk assessment indicates that public health most likely would be impacted by well completion activities, particularly for residents living nearest the wells. Based on this information, suggested risk prevention strategies in the HIA are directed at minimizing exposures for those living closet to the well pads, especially during well completion activities when emissions are the highest. The HIA includes recommendations to (1) control and monitor emissions during completion transitions and flowback; (2) capture and reduce emissions through use of low or no emission flowback tanks; and (3) establish and maintain communications regarding well pad activities with the community (Witter et al., 2011).

4.3. Comparisons to other risk estimates

This risk assessment is one of the first studies in the peer-reviewed literature to provide a scientific perspective to the potential health risks associated with development of unconventional natural

Table 6
Excess cancer risks for residents living >½ mile from wells and residents living ≤½ mile from wells.

Hydrocarbon	WOE		Unit Risk (μg/m^3)	Source	>½ mile		≤½ mile	
	IRIS	IARC			Cancer risk based on median concentration	Cancer risk based on 95% UCL of mean concentration	Cancer risk based on median concentration	Cancer risk based on 95% UCL of mean concentration
1,3-Butadiene	B2	1	3.00E−05	IRIS	1.30E−06	5.73E−07	1.30E−06	6.54E−07
Benzene	A	1	7.80E−06	IRIS	3.03E−06	5.40E−06	3.33E−06	8.74E−06
Ethylbenzene	NC	2B	2.50E−06	CalEPA	1.75E−07	4.26E−07	2.09E−07	3.48E−06
Styrene	NC	2B	5.00E−07	CEP	3.10E−08	2.70E−08	3.00E−08	9.30E−08
Cumulative cancer risk					5E−06	6E−06	5E−06	1E−05

Abbreviations: 95%UCL, 95% upper confidence limit; CalEPA, California Environmental Protection Agency; CEP, (Caldwell et al., 1998); IARC, International Agency for Research on Cancer; IRIS, Integrated Risk Information System; Max, maximum; NC, not calculated; WOE, weight of evidence; μg/m^3, micrograms per cubic meter. Data from CalEPA 2011; IRIS (US EPA, 2011).

gas resources. Our results for chronic non-cancer HIs and cancer risks for residents > than ½ mile from wells are similar to those reported for NGD areas in the relatively few previous risk assessments in the non-peer reviewed literature that have addressed this issue (CDPHE, 2010; Coons and Walker, 2008; CDPHE, 2007; Walther, 2011). Our risk assessment differs from these previous risk assessments in that it is the first to separately examine residential populations nearer versus further from wells and to report health impact of emissions resulting from well completions. It also adds information on exposure to air emissions from development of these resources. These data show that it is important to include air pollution in the national dialogue on unconventional NGD that, to date, has largely focused on water exposures to hydraulic fracturing chemicals.

4.4. Limitations

As with all risk assessments, scientific limitations may lead to an over- or underestimation of the actual risks. Factors that may lead to overestimation of risk include use of: 1) 95% UCL on the mean exposure concentrations; 2) maximum detected values for 1,3-butadiene, 2,2,4-trimethylpentane, and styrene because of a low number of detectable measurements; 3) default RME exposure assumptions, such as an exposure time of 24 h per day and exposure frequency of 350 days per year; and 4) upper bound cancer risk and non-cancer toxicity values for some of our major risk drivers. The benzene IUR, for example, is based on the high end of a range of maximum likelihood values and includes uncertainty factors to account for limitations in the epidemiological studies for the dose–response and exposure data (US EPA, 2011). Similiarly, the xylene chronic RfC is adjusted by a factor of 300 to account for uncertainties in extrapolating from animal studies, variability of sensitivity in humans, and extrapolating from subchronic studies (US EPA, 2011). Our use of chronic RfCs values when subchronic RfCs were not available may also have overestimated 1,3-butadiene, n-propylbenzene, and propylene subchronic HQs. None of these three chemicals, however, were primary contributors to the subchronic HI, so their overall effect on the HI is relatively small.

Several factors may have lead to an underestimation of risk in our study results. We were not able to completely characterize exposures because several criteria or hazardous air pollutants directly associated with the NGD process via emissions from wells or equipment used to develop wells, including formaldehyde, acetaldehyde, crotonaldehyde, naphthalene, particulate matter, and polycyclic aromatic hydrocarbons, were not measured. No toxicity values appropriate for quantitative risk assessment were available for assessing the risk to several alkenes and low molecular weight alkanes (particularly $<C_5$ aliphatic hydrocarbons). While at low concentrations the toxicity of alkanes and alkenes is generally considered to be minimal (Sandmeyer, 1981), the maximum concentrations of several low molecular weight alkanes measured in the well completion samples exceeded the 200–1000 $\mu g/m^3$ range of the RfCs for the three alkanes with toxicity values: n-hexane, n-pentane, and n-nonane (US EPA, 2011; ORNL, 2009). We did not consider health effects from acute (i.e., less than 1 h) exposures to peak hydrocarbon emissions because there were no appropriate measurements. Previous risk assessments have estimated an acute HQ of 6 from benzene in grab samples collected when residents noticed odors they attributed to NGD (CDPHE, 2007). We did not include ozone or other potentially relevant exposure pathways such as ingestion of water and inhalation of dust in this risk assessment because of a lack of available data. Elevated concentrations of ozone precursors (specifically, VOCs and nitrogen oxides) have been observed in Garfield County's NGD area and the 8-h average ozone concentration has periodically approached the 75 ppb National Ambient Air Quality Standard (NAAQS) (CDPHE, 2009; GCPH, 2010).

This risk assessment also was limited by the spatial and temporal scope of available monitoring data. For the estimated chronic exposure, we used 3 years of monitoring data to estimate exposures over a 30 year exposure period and a relatively small database of 24 samples collected at varying distances up to 500 ft from a well head (which also were used to estimate shorter-term non-cancer hazard index). Our estimated 20-month subchronic exposure was limited to samples collected in the summer, which may have not have captured temporal variation in well completion emissions. Our ½ mile cut point for defining the two different exposed populations in our exposure scenarios was based on complaint reports from residents living within ½ mile of existing NGD, which were the only data available. The actual distance at which residents may experience greater exposures from air emissions may be less than or greater than a ½ mile, depending on dispersion and local topography and meteorology. This lack of spatially and temporally appropriate data increases the uncertainty associated with the results.

Lastly, this risk assessment was limited in that appropriate data were not available for apportionment to specific sources within NGD (e.g. diesel emissions, the natural gas resource itself, emissions from tanks, etc.). This increases the uncertainty in the potential effectiveness of risk mitigation options.

These limitations and uncertainties in our risk assessment highlight the preliminary nature of our results. However, there is more certainty in the comparison of the risks between the populations and in the comparison of subchronic to chronic exposures because the limitations and uncertainties similarly affected the risk estimates.

4.5. Next steps

Further studies are warranted, in order to reduce the uncertainties in the health effects of exposures to NGD air emissions, to better direct efforts to prevent exposures, and thus address the limitations of this risk assessment. Next steps should include the modeling of short- and longer-term exposures as well as collection of area, residential, and personal exposure data, particularly for peak short-term emissions. Furthermore, studies should examine the toxicity of hydrocarbons, such as alkanes, including health effects of mixtures of HAPs and other air pollutants associated with NGD. Emissions from specific emission sources should be characterized and include development of dispersion profiles of HAPs. This emissions data, when coupled with information on local meteorological conditions and topography, can help provide guidance on minimum distances needed to protect occupant health in nearby homes, schools, and businesses. Studies that incorporate all relevant pathways and exposure scenarios, including occupational exposures, are needed to better understand the impacts of NGD of unconventional resources, such as tight sands and shale, on public health. Prospective medical monitoring and surveillance for potential air pollution-related health effects is needed for populations living in areas near the development of unconventional natural gas resources.

5. Conclusions

Risk assessment can be used as a tool in HIAs to identify where and when public health is most likely to be impacted and to inform risk prevention strategies directed towards efficient reduction of negative health impacts. These preliminary results indicate that health effects resulting from air emissions during development of unconventional natural gas resources are most likely to occur in residents living nearest to the well pads and warrant further study. Risk prevention efforts should be directed towards reducing air emission exposures for persons living and working near wells during well completions.

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Exhibit 43.01

This exhibit was not previously submitted in November 2023

Commission NORM Survey of Equipment at Leases and Facilities

Fields With Equipment Readings >50 MR/Hr

Staff of the Commission district offices performed field surveys from December 1999 to mid-March 2000. The purpose of the survey was to measure levels of NORM in equipment being used at production leases and other associated oilfield facilities to estimate the number of sites at which NORM-contaminated equipment may be located and to estimate an approximate range of the level of NORM at various sites across the state. The leases were chosen randomly to ensure a representative sample. Measurements were collected using an energy-compensated pulse rate “micro-R” meter that provides a scaled reading in microroentgens per hour (μR/hr.) Equipment measurements were taken at locations where gamma radiation most likely would be detected if present such as flow lines, tanks/vessels, pipe, pumps, valves, and injection headers. Background readings were also collected for comparison. More than 5,900 readings were collected on more than 600 leases and other oil and gas facilities.

Most of the readings of oil and gas equipment collected during the field survey demonstrate that the radiation levels are typically below the regulatory limit for release of equipment for unrestricted use (use for purposes other than oil and gas activities.) Of the 612 sites surveyed, only 59 sites had equipment with readings above 50 μR/hr, the limit above which the equipment cannot be released for unrestricted use. Out of over 5,900 readings, only 203 readings were above 50 μR/hr. The survey, however, indicates that specific geographic areas tend to have elevated NORM levels. The geographic distribution is evident from the randomly selected leases and facilities surveyed in each commission district at which NORM readings of equipment were greater than 50μ/hr.

No readings greater than 50 μR/hr were found for equipment on leases/facilities in RRC Districts 1 and 8A.

Filter this table:

RRC District	County	Field	# Equipment Readings 50 μR/hr	Maximum Reading (μR/hr)
02	Karnes	Person (Edwards)	2	56
02	Karnes	Panna Maria (Edwards)	4	400
03	Chambers	Devillier (Vicksburg)	1	60
04	Brooks	Pita (A-8)	1	155

RRC District	County	Field	# Equipment Readings 50 μR/hr	Maximum Reading (μR/hr)
04	Hidalgo	McAllen Ranch (Guerra)	3	92
04	Hidalgo	McAllen Ranch (Guerra E)	3	250
04	Kenedy	Sarita, East (0-Sand)	2	117
04	Kenedy	Rita (S.M. North)	8	230
04	Nueces	Turkey Creek (4000 Sand)	7	320
04	Willacy	Willamar, West	16	200
05	Henderson	Opelika (Woodbine) (SWD Fac.)	4	212
05	Van Zandt	Fruitvale	3	130
05	Van Zandt	Grand Saline	3	350
05	Leon	Jewitt (Travis Peak)	2	90
06	Cass	Linden, East (Cotton Valley)	1	75
06	Gregg	Willow Springs (Travis Peak)	1	57
06	Panola	Bethany (Rodessa) SWD Fac	5	67
06	Rusk	New London (Travis Peak)	2	75
06	Smith	Overton (Travis Peak)	1	132
06	Wood	Quitman (Paluxy)	1	550
06	Wood	Quitman (Eagle Ford)	1	550
08	Loving	Wheat (Cherry Canyon)	4	1100
08	Midland	Spraberry (Trend Area)	5	500

RRC District	County	Field	# Equipment Readings 50 µR/hr	Maximum Reading (µR/hr)
08	Reeves	Collie (Delaware)	5	275
08	Reeves	Ken Reagan (Delaware)	2	56
08	Ward	Rhoda Walker (Canyon 5900)	5	812
08	Winkler	Evetts (Silurian)	1	150
09	Archer	Trans-continental (VOGTS. 4500)	2	247
09	Archer	Archer County Regular	1	125
09	Clay	Clay County Regular	1	75
09	Wichita	Wichita County Regular	5	313
09	Wilbarger	Wilbarger County Regular	1	125
10	Wheeler	Mobeetie (Missouri Basal)	11	117
10	Hutchinson	Hutch (Penn 5650)	4	77
10	Hutchinson	Bar Nine (Council Grove)	6	300
10	Gray	Hoover, NE (Ellenburger)	1	54
7B	Comanche	Duster, NE (Marble Falls 2750)	2	73
7B	Throckmorton	Throckmorton County Regular	4	252
7C	Coke	Jameson (Strawn)	3	400
7C	Coke	Bloodworth, NE (5750 Canyon)	4	117
7C	Coke	IAB (Menielle Penn.)	1	88
7C	Coke	Ft. Chadbourne	3	360

RRC District	County	Field	# Equipment Readings 50 μR/hr	Maximum Reading (μR/hr)
7C	Crockett	Weger, N. Commercial SWD	7	250
7C	Irion	Brooks (San Angelo)	3	90
7C	Reagan	Spraberry (Trend Area) Commercial SWD	9	225
7C	Reagan	Spraberry (Trend Area)	10	550
7C	Runnels	Ballinger (Palo Pinto, N)	2	300
7C	Runnels	Ballinger (Palo Pinto) Commercial SWD	9	900
7C	Runnels	Busher (Morris)	2	90
7C	Schleicher	Camar, N (Canyon Sand)	2	105
7C	Schleicher	Hulldale, W (Harkey) Commercial SWD	10	910
7C	Sutton	Sonora, SE (Canyon Reef) Commercial SWD	9	300
7C	Sutton	Ft. Terrett Ranch (Canyon 2800)	1	52
7C	Tom Green	Giebel (Strawn) Commercial SWD	9	450
7C	Tom Green	Harriett Commercial SWD	7	425
7C	Upton	Spraberry (Trend Area)	7	167
7C	Upton	Amacher	3	166

Showing 1 to 57 of 57 entries

Exhibit 43.02

This exhibit was not previously submitted in November 2023

Where Does All The Radioactive Fracking Waste Go?

Justin Nobel

On May 8, 2017, a drum of radioactive oilfield waste from Australia arrived at a remote West Texas disposal site operated by local oil and gas environmental services company, Lotus LLC. This drum of waste entered the United States aboard a Singapore Airlines cargo jet, appropriately packaged in a steel drum. According to files from the Railroad Commission of Texas, the state's main oil and gas regulator, it contained the radioactive element radium at concentrations of 2,095 picocuries per gram. Those levels are more than 400 times the protective health limits designated by the U.S. Environmental Protection Agency (EPA) for toxic Superfund sites and uranium mills, where fuel for nuclear bombs was once assembled.

The oil and gas industry produces an extraordinary amount of waste. Much of it is toxic, and it can be highly radioactive too. And since 1997 about one million barrels worth of oilfield waste has been brought to Lotus's disposal site, situated off a dusty desert road located 19 miles west of Andrews, Texas (and just several miles from a massive solar array financed by Facebook and which provides energy to Shell's fracking operations).

But according to correspondence with federal and state regulators, documents obtained via a Freedom of Information Act (FOIA) request, and interviews with an industry whistleblower, DeSmog has found that the Lotus disposal site has at times struggled to safely manage the radioactive waste it receives from across the United States.

Despite this challenge, it is importing oil and gas waste from other countries too, and is expanding its reach internationally.

The company has relied heavily on a decades-old industry exemption passed in 1980 — known as the Bentsen and Bevill Amendments to the Resource Conservation and Recovery Act — that classifies oil and gas waste as non-hazardous, thereby affording it little regulatory scrutiny. Meanwhile, Railroad Commission documents obtained via a FOIA request suggest that practices at Lotus's remote disposal site have put the company's workers and the environment at risk.

Lotus LLC office and truck yard in Andrews, Texas, in April 2021. Credit: Justin Hamel ©2021

“The oil and gas industry has been really good at painting the picture that they are not a radioactive industry,” said Melissa Troutman, an Earthworks analyst and author of a 2019 report on oil and gas waste, “when in reality it produces a massive amount of radioactive material.”

A growing group of environmentalists, politicians, communities, and even the industry’s own workers have become increasingly critical of the fossil fuel industry, and see room for action under the Biden administration, though most attention has been placed on hot-button topics like climate change and methane emissions. But a small yet ardent band of advocacy groups have been focused on radioactive oilfield waste, long an industry problem but one that has metastasized in the fracking boom and potentially poses an even greater risk to the industry’s bottom line.

Financed by Facebook and powering Shell fracking operations, the Prospero 1 solar field lies just a few miles from the Lotus disposal site in Andrews County, Texas. Adjacent is the Prospero 2 project, whose power has been purchased by a medical services company. Credit: Justin Hamel ©2021

"Waste is the Achilles' heel for these guys," said Ted Auch, an analyst who has been closely tracking oilfield waste with the watchdog group FracTracker Alliance. "The entire industry operates on the notion that this stuff is relatively cheap and easy to get rid of. If they ever had to pay full price for the waste they produce, the industry's cost-calculus crumbles."

According to one calculation in a 2013 analysis co-authored by nuclear physicist and radioactive waste specialist, Marvin Resnikoff, if oil and gas waste were appropriately characterized, disposal costs could increase by more than half a million dollars for every well drilled.

DeSmog's investigation raises serious concerns as to whether the waste being shipped to Lotus is being disposed of properly.

"If the industry was not exempt from hazardous waste law," said Troutman, "the characterization of their waste would be far better, the tracking would be far better, and it would be harder for companies to manipulate the system like this."

Who Is Lotus LLC?

The EPA says the oil and gas industry generates an estimated 5 million cubic feet of radioactive sludge a year, much of it in tanks at the wellhead. That's enough to fill an Olympic-size swimming pool every week, and this figure only includes sludge generated from conventionally drilled wells.

A radioactive "scale" forms on the inside of wellhead piping, and sludge and radioactive films that are often invisible to the naked eye also accumulate inside natural gas and natural gas liquids pipelines and processing equipment. According to a 1993 paper published by the Society of Petroleum Engineers, much of this material "must be handled as low-level radioactive waste and disposed of accordingly."

While oil and gas waste may be considered non-hazardous under the Bentsen and Bevill Amendments, it is often too radioactive to be disposed of in a typical landfill. This is where special disposal at sites like Lotus come in, along with a handful of others across the country that are licensed to handle radioactive oilfield waste, including US Ecology in Idaho and Energy Solutions in Utah.

Lotus, a private company with about 75-100 employees, has permits from the Railroad Commission of Texas that enables the waste to be unloaded into pits, and crushed and mixed with water to form a slurry that can be more easily injected down a set of injection wells and into a salt cavern. When properly prepared, these massive domes of salt beneath the earth can be used as a subterranean locker, and the Department of Energy has deemed this an appropriate option for the disposal of radioactive oilfield waste. But Railroad Commission reports, such as one 2003 inspection, indicate that the waste is not always making it into the salt cavern, and rather Lotus “is only using the entire facility plant and decon facility for storage.”

- According to an anonymous industry insider, a type of oilfield waste known as “pipe scale” appears to be stored in these tanks at the Lotus facility around 2015-2016. Both tanks are marked with yellow radioactivity placards.

- An industry insider with extensive experience in oilfield waste disposal showed concern about observing the apparent "stockpiling," rather than processing and underground injection, of radioactive oilfield waste at the Lotus facility around 2015-2016.

The whistleblower corroborated this critique of Lotus, and described a situation during an informal visit in the time period of 2015 to 2016 in which the Lotus site had been overrun with stockpiled waste, with barrels piled up around the site. A longtime executive in the oilfield waste industry with firsthand knowledge of disposal facilities across the country, this whistleblower has requested anonymity due to ongoing industry legal obligations. They provided DeSmog with photos of the Lotus site from that period which convey damaged, rusty tanks marked with a yellow radioactivity symbol, a heaped dumpster of additional waste material, and several unmarked black barrels sitting on wooden pallets, without any liners or containment to prevent leaching or runoff. The whistleblower called the Lotus site "alarming and a potential environmental disaster for Texas" and "one of the most shocking facilities I have ever seen in my time in the oil and gas industry."

DeSmog sent the photos to James Dillingham, the director of global operations with Lotus, who replied with a series of comments. Dillingham stated the photos "are not representative of how Lotus, LLC manages waste. These photos only illustrate a single instance where material was received and was under process for disposal, which was within the parameters of our licenses and permits." Dillingham added, "Representing Lotus by way of publishing wording or photos in a manner that causes the public to conclude that material sent to our facility is or was handled otherwise will be considered libel. Accordingly, we will seek restitution under the law for personal and financial injury caused by any misrepresentation caused by this."

- Lotus executive James Dillingham told DeSmog that these photos taken around 2015-2016 “are not representative of how Lotus, LLC manages waste. These photos only illustrate a single instance where material was received and was under process for disposal, which was within the parameters of our licenses and permits.”

- A number of uncovered containers, open to the elements and sometimes showing damage and rust, appear to hold radioactive oilfield waste at the Lotus LLC facility around 2015-2016.

Additionally, Dillingham supplied a response on behalf of his manager: “The pictures that are proposed to be presented in the article as previously poised are the property of Lotus LLC and are copyrighted and we don’t give permission to display those in any form or fashion and must be returned to us immediately. Additionally the entity or person who has conveyed these pictures to you or has somehow allowed them to become in your possession has violated the confidentiality clause they signed up for and their identity must also be revealed to us so that appropriate legal action may be conducted should these photos be publicly displayed and not returned or destroyed. You are requested to resolve this issue immediately so as to prevent further harm.”

Dillingham also stated that, “according to my manager, the photos you have provided are outdated and not an accurate representation of what is currently at the facility.”

On Sunday, April 4, 2021, DeSmog sent a photographer over the Lotus site in a small plane. The photos reveal the site contains a significant number of stockpiled barrels and containers. When the whistleblower reviewed these recent photos, they said the images suggest that many of the same issues remain — and may have worsened — since their earlier site observation at the Lotus facility during the 2015-2016 timeframe. They pointed to what appeared to be significant amounts of stockpiled TENORM wastes held in numerous damaged, rusted, and degraded tanks or barrels stored directly on an unlined surface without proper containment to prevent leaching, runoff, and other direct risks to groundwater and surface contamination.

A longtime industry insider, after observing photos of the Lotus site from 2021, said that it appeared that compliance issues remained, possibly including a lack of proper containment around the site, a lack of liners, and large amounts of oilfield waste that have yet to be processed or properly disposed. Credit: Justin Hamel ©2021

The whistleblower also noted that many of the large open tanks in the photos appeared to show high volumes of filter socks and scale from pipes used during oilfield operations — both filter socks and pipe scale are known to have a high radioactive signature. The whistleblower said these were apparent compliance issues, with possible violations including a lack of proper containment around the site, lack of lined protection to the surface, and significant volumes of stockpiled TENORM wastes that have yet to be processed or properly disposed.

“I can’t confirm these pictures,” Lotus operation manager Dan Snow replied via email. In response to questions about the nature of the stockpiled waste and alleged violations, Snow said, “as always, our plant is in full production mode handling all types of RCRA exempt waste as it is shipped to the facility. Waste comes in all types of packaged and unpackaged methods and it can even come in a dump truck so long as the transporter follows the DOT [Department of Transportation] and RRC rules. Waste may even come in the form of abandoned vessels that have to be taken apart to remove the waste.” Snow stated Lotus operations follow all appropriate state and federal rules and permits.

DeSmog sent the recent aerial photos to the RRC for review and asked the agency to comment on the alleged violations and compliance issues. “Our agency conducts inspections to ensure compliance with all rules in place to protect public safety and the environment,” said R.J. DeSilva, the RRC Director of Communications. He directed DeSmog to a web portal that features inspection information for oilfield facilities. It shows that the most recent RRC inspection of the Lotus site in Andrews County occurred on March 29, 2021 and found no compliance issues, stating, “No violations were observed in this inspection.”

Files from the Railroad Commission of Texas, the state oil and gas regulator, indicate that virtually every major operator in the oil and gas industry has sent their waste to Lotus, including ExxonMobil, BP, and Chevron. Credit: Justin Hamel ©2021

Every single day, hundreds of barrels of oilfield waste may arrive via truck at Lotus. The waste comes from oil and gas fields across Texas (including a set of wells operated by Chesapeake and located on the grounds of the Dallas/Fort Worth International Airport) and neighboring states like New Mexico, Oklahoma, and Louisiana. It also comes from offshore wells in the Gulf of Mexico and some of the last remaining oil and gas platforms off the California coast, operated by ExxonMobil. The waste arrives from states as far as Alaska, North Dakota, Michigan, Colorado, West Virginia, and Pennsylvania, and even states like Minnesota, Wisconsin, and Iowa, which have no significant oilfields but are crisscrossed by pipelines that fill up with radioactive sludge. The Railroad Commission files indicate that radioactive sludge also builds up at compressor stations, and this waste may be shipped to Lotus.

The files indicate that virtually every major operator in the oil and gas industry has sent their waste to Lotus, including ExxonMobil, BP, Chevron, Occidental, Anadarko, ConocoPhillips, Chesapeake, as well as midstream companies like Kinder Morgan and ONEOK. DeSmog reached out to these companies who were mostly unresponsive to questions about the site and its operating practices. “At BP we remain committed to safe, reliable, and compliant operations,” stated Cameron Nazminia, Corporate Communications Manager with BP, one of the few companies that replied to questions about Lotus.

> “These operators took a lot and got in over their heads.”
>
> A longtime oilfield waste industry insider on Lotus LLC

While the process of grinding radioactive waste into a slurry and injecting it down a hole may seem simple, the whistleblower explained that performing the process safely is technically challenging and operationally expensive. Radioactive oilfield waste is referred to as NORM, or TENORM (Technologically Enhanced Naturally Occurring Radioactive Materials), and a facility licensed to dispose of it can charge waste generators high disposal fees, sometimes as high as $200-250 per barrel, versus an average of around $8 per barrel at a facility simply licensed to dispose of the industry’s non-radioactive waste, according to the whistleblower.

“What happened is they just got overrun with TENORM waste material being delivered from all over the country,” the whistleblower said of Lotus, “they were not technologically or operationally capable, and did not properly manage what was accepted for disposal at the facility. These operators took a lot and got in over their heads.”

The Lotus LLC disposal facility outside of Andrews, Texas, has received approximately one million barrels of oilfield waste since opening in 1997. Credit: Justin Hamel ©2021

James Dillingham, the director of global operations with Lotus, said that, “Any NORM contaminated material present at the site is being processed in accordance with our license and permits.” He said that in recent years, “we have been able to increase daily capacity by having more employees, more offload areas, more efficient pumps, and better process knowledge.” He also pointed out that Lotus was licensed to receive all manners of “nonhazardous oil and gas waste” and that not all of the waste it received was radioactive. “I only say that to illustrate the fact that the items that appear to be accumulating may not necessarily be classified as radioactive waste, nor a waste that has other hazardous elements,” he said.

According to the company’s own quarterly reports to the Railroad Commission, Lotus took in over 10 times more waste in 2013 (83,895 barrels) compared to a decade earlier (6,673 barrels in 2003). When asked how the company has been able to handle the enhanced waste stream brought on by the fracking boom, Dillingham said, “We are currently investing heavily in new technology that will help us process the more difficult types of waste that are plaguing the industry.”

“We believe this technology will allow us to provide a more economical yet equally as secure solution to the industry,” he added. “In the meantime, any difficult or time-consuming materials requiring extended processing are securely temporarily stored in a restricted area adjacent to the processing/disposal facility with constant surveillance, air monitoring, and dosimetry.” (Dosimetry refers to the science of measuring the radiation dose absorbed by the human body.)

Furthermore, he added, the facility is subject to annual audits by the Railroad Commission, the Texas Department of State Health Services, clients, and other groups, and also “more frequent surprise audits.” “These audits would reveal any discrepancy between the Lotus operation and the items that are allowed under the licenses and permits while also obviously revealing any potential weak points that could cause increased risk to human health and safety,” he told DeSmog.

A Risk to Workers

But as the more than 2,000 pages of records and reports reviewed by DeSmog show, Lotus has experienced a number of concerning incidents that began shortly after the site opened in 1997. This history includes radioactive waste leaking into the ground and barrels of waste regularly being piled on site for extended periods of time. Local community members also raised concerns about workers being exposed to radioactivity.

One particularly damning Railroad Commission inspection occurred in May 2003. "There were several metal drums with corroded sides and/or bottoms located at various spots within the fenced process facility," states the report. "The deteriorated condition of these drums has allowed some NORM contents to escape to the ground." The inspection suggested that rain received in the days prior to inspection had carried contamination to "low lying, muddy areas near the gate."

Handwritten notes in the May 2003 report show that drums of waste had been moved around the site "only for the purpose of a cosmetic coverup," again suggesting the waste was not being appropriately disposed of by injection into the salt cavern, but instead being stored on the site's grounds. Furthermore, the notes express concern that one of the injection wells has been inappropriately "abandoned" and that the "casing perhaps could be corroded/wear away gradually" and if the well were not properly isolated, the situation could "be harmful to our drinking water."

In May 2004, Railroad Commission Assistant District Director Mike Houston visited the Lotus facility and noted, "There are still some pollution concerns." On a walkthrough inspection, Houston noticed "leaking steel drums" whose contents had "either partially spilled or [had] the immediate possibility of leaking onto the storage yard soils." The letter stated that the conditions observed violated Texas Statewide Rule 8, which regards water pollution and oilfield waste pits.

The report also addressed worker radioactivity risks: One steel drum at the Lotus site measured 5,800 microrems per hour — a measurement used to classify how much radioactivity would be absorbed by a human being — an amount "which can be a health threat to coworkers, given extended exposure time."

When DeSmog ran that number by Worcester Polytechnic Institute nuclear forensics scientist Marco Kaltofen, he explained that the level was worrisome. "At 5,800 microrems an hour, it would take only about two days to get your typical ANNUAL dose of industrial/medical radiation," Kaltofen stated in an email, referencing dose limits set by the Nuclear Regulatory Commission for the nuclear and medical industries. These limits, however, do not apply to oil and gas workers.

But perhaps most concerning among the public records DeSmog received from the Railroad Commission was a letter sent to the regulatory agency in October 2000 by the "Concerned Citizens of Andrews County, Texas."

"We regret having to write you [a] letter anonymously, but because of the nature of the individual involved, we fear not only reprisal from him personally, but also from his battery of attorneys," the letter states.

The Concerned Citizens explain that they "have made trips to a facility operated by Lotus, L.L.C. in western Andrews County" and found drums of radioactive waste stacked along the fence line of the facility, "a large pile of dirt and rocks on the north fence line that appears to be radioactive contaminant as well," and a trio of 500-barrel frac tanks that "are completely full of what appears to be radioactive waste."

According to the letter, Lotus workers told the Concerned Citizens that some of this waste had been stored on site "in excess of two years." The Railroad Commission was not able to provide a direct response to the question of how long waste is allowed to sit on site before having to be disposed of down the injection well and into the salt cavern.

"These employees have also expressed concerns for their health from long term exposure to this material," the letter adds.

Attempts to locate the authors of the anonymous letter were not successful. DeSmog presented the letter to Lotus, along with a copy of the June 2003 inspection report that noted leaking waste barrels.

"As it relates to the concerns presented in the letter, the citizens are certainly entitled to bring awareness to potential problems; however, in this particular case, it does not appear that there was anything that was causing any elevated health, safety, or environmental risk," said Dillingham.

He also defended the company's efforts to protect its workers from radioactivity contamination. "I can confirm that at the time of the filing, and continuing through today, all employees whose job duties involve potentially making an entry into a restricted area are monitored in the dosimetry program outlined in the Lotus Health Physics Plan," said Dillingham. "As a company that is licensed for handling this type of waste we have our own health physics plan in place…Lotus workers work around NORM all day, every day, and given that we have never had a person exceed the dose limit, ever, and we have been in business since 1997."

But Texas regulators do not appear to be addressing the worker safety questions raised in the files received from the Railroad Commission.

DeSmog informed the Texas Department of State Health Services (DSHS) that Lotus records indicate sloppy operating practices that put both workers and the environment of Texas at risk. “DSHS does not regulate the Lotus disposal site,” replied Chris Van Deusen, the agency’s Director of Media Relations.

When asked by DeSmog what tests, inspections, or surveys DSHS has conducted of Lotus workers to ensure they are appropriately protected from radioactivity, Van Deusen again stated, “DSHS does not regulate the Lotus disposal site.” OSHA, in previous correspondence with DeSmog, has conveyed that oilfield workers are not at risk from radioactivity, yet the agency has never formally studied the issue.

“These operators took a lot and got in over their heads,” a longtime industry insider told DeSmog of Lotus’s operating practices for radioactive oil and gas waste. Credit: Justin Hamel ©2021

The whistleblower expressed concern that Lotus “poses a black eye” to the oil and gas industry and Texas regulators.

“It is exceedingly maddening that nothing is actively being done to properly address these issues,” said the whistleblower. “Myself and others have been pounding the table on this and speaking with the Railroad Commission in Texas for nearly 10 years now. It is there, everyone knows about it, and no one can say they don’t know. Yet, the regulators have not taken any meaningful efforts to correct this dangerous and poor operating practice.”

Importing Radioactive Waste

A lack of oversight when it comes to domestic waste, however, isn’t the only challenge. The 1980s industry exemption also makes it easier to import radioactive oil and gas waste produced outside the United States.

Because this waste is generated in an oilfield, unlike radioactive waste generated by the nuclear or medical industries, the notorious Bentsen and Bevill Amendments enables it to move around the U.S. insufficiently monitored — and into the U.S. from other parts of the world entirely unmonitored.

In DeSmog’s correspondence with EPA, the Nuclear Regulatory Commission, and the Railroad Commission of Texas, it has become apparent that no federal or state agency appears to be tracking or monitoring shipments of radioactive oilfield waste into the United States from foreign countries, and none of these agencies appear to have regulatory authority over such international shipments. U.S. Customs and Borders Protection has not responded to questions on the matter.

Lotus LLC is importing radioactive oilfield waste from outside the United States and is looking to expand its international operations. Credit: Justin Hamel ©2021

According to Jeff Tyson, Head of Environmental Research and Analytics with the Texas-based firm Waste Analytics, oilfield waste generated in Mexico, for example, has been transported across the border for disposal in the United States. At least 534 loads of waste, said Tyson, was transported between October 2005 and March 2006, and disposed of at a treatment facility in Starr County, Texas.

Lotus's first international shipment was 65.5 barrels of soil and sludge that arrived from Alberta, Canada in November 1999. The files DeSmog obtained from the Railroad Commission records request reveal that more than 450 barrels of waste from Canada arrived between 1999 and 2004.

Information provided to DeSmog by Dillingham shows that Lotus had imported 750 barrels of oilfield waste from Australia between May 2017 and November 2019 — the first barrel arrived by plane, the rest have been transported by ship.

"We reached out to the EPA and the NRC asking if there were any objections to importing Resource Conservation Recovery Act (RCRA) exempt E&P waste containing diffuse amounts of NORM," said Dillingham. But as DeSmog has learned, no specific permits appear to be necessary in order to import radioactive oilfield waste into the country.

Presently, Lotus is in the process of expanding its overseas operations. The company has already established an office in Watford, England, part of a joint venture tasked with decommissioning, decontamination, and waste management services to the oil and gas and industrial sectors in Europe, UK, and Russia. A map passed along by Dillingham conveys that Lotus has a presence in oilfields on every continent but Antarctica. "Our international services include NORM training, surveying, consulting, decontamination and a whole gambit of other non-NORM related services relating to decommissioning and well servicing," said Dillingham. "As it relates to importing NORM waste, it has never been our long-term strategy. The ability to import a stockpiled volume of material can help solve an immediate need, but the long-term objective is to help countries develop local solutions."

Wording on the website of the company's England-based joint venture, Lotus ZRG, appears to promote Lotus's disposal site in Andrews, Texas: "Welcome to Lotus ZRG – from our licensed facility in Texas, we provide NORM decontamination, transportation and disposal internationally to wherever our clients' facilities require us."

Current federal laws give the company confidence that these imports are legitimate. "As it relates to transportation, the requirements are based on the same regulations for road or by ship," said Dillingham. "I certainly didn't intend on implying or stating that it wasn't regulated. I said that it is not federally regulated. NORM waste is not defined as a 'radioactive waste' by the NRC, therefore not under the Atomic Energy Act. Further, wastes strictly associated with the exploration and production of oil & gas are exempt from EPA hazardous waste definitions under RCRA. Wastes meeting this exemption are regulated on the state level."

When Lotus asked the EPA in an October 12, 2016 email whether or not the company could import radioactive oilfield waste, the agency replied on November 7, 2016, stating: "Based solely on the information provided by Lotus, the waste…is exempted from federal hazardous waste regulations" and "as such…may be imported to the United States without a hazardous waste notification." The Railroad Commission, in a December 2016 report, recognizes that "EPA does not regulate the waste" and states that Lotus's permits with the state agency do not "require or restrict the acceptance of offshore (outside US waters) or foreign oil & gas waste."

A 2018 letter from the Nuclear Regulatory Commission stated that because the federal agency has no regulatory authority over the oil and gas industry's radioactive materials, "it would not meet the…definition of radioactive waste."

"EPA has no records of Lotus importing oilfield waste," stated an EPA spokesperson, and the agency is not keeping track of how much foreign oilfield waste is entering the U.S., how it enters the country, at which port it enters, or how radioactive it is.

"As we lack jurisdiction over this material," Nuclear Regulatory Commission spokesperson David McIntyre told DeSmog, "we do not track its movement or disposal."

More than half a dozen other analysts and policymakers DeSmog spoke to for this story were unaware that oilfield waste was being imported into the United States.

"It never occurred to me that we might be importing toxic and radioactive oil and gas waste from other countries," said Amy Mall, a senior advocate with the environmental group Natural Resources Defense Council (NRDC). Mall has been tracking oil and gas waste and its impacts for over a decade and is set to release a new report on the topic with NRDC shortly. "Americans are used to the situation where we're the ones shipping waste overseas to other people who don't have the ability to stop it, but in this case that has been reversed," said Mall.

"I do a lot of consulting on import and export of radioactive material and frankly I don't think there is any database anyone maintains to know what goes in and out of the country," said Rick Jacobi, the owner and principal consultant at Jacobi Consulting, a former General Manager of the Texas Low-Level Radioactive Waste Disposal Authority and current consultant for domestic and international companies on the management of radioactive material and nuclear facilities. "I don't think that U.S. Customs maintains any database, and to my knowledge there is no national database."

None of the regulatory agencies in Texas involved in oil and gas, including the Railroad Commission, the Texas Department of State Health Services, or the Texas Commission on Environmental Quality, have "jurisdiction over the import or export of radioactive waste," Jacobi added. "Imports and exports are regulated exclusively by the federal government."

"Commercial facilities have a financial incentive to accept the waste and generate revenue regardless of where the waste was generated," added Jeff Tyson, with Waste Analytics. "As long as the facility is permitted to accept the waste, there is no legal or economic reason for them to reject it."

Meanwhile, there may be the need for a much larger investigation. "Companies who are licensed to deal with this waste are trying their best to provide a responsible solution but are often the only ones who get criticized or reviewed," said Dillingham. "The bigger problem is those who don't even bother to get licensed and protect their staff." He said the oilfields of Texas and Oklahoma contain several large facilities of this nature, which accept NORM waste without licenses or proper screening controls in place. Dillingham adds that Lotus's salt cavern is approaching capacity, and the company is presently in the process of creating another one — using a process called solution mining — out of the bedded salt deposit at the property in Andrews County. Once permitted for waste disposal it could have disposal capacity for up to another million barrels of oilfield waste.

Exhibit 46.01

This exhibit was not previously submitted in November 2023

DMS - 11000

EVALUATING AND USING NONHAZARDOUS RECYCLABLE MATERIALS GUIDELINES

EFFECTIVE DATE: OCTOBER 2008

11000.1. Description. This Specification governs the process for evaluating the environmental factors associated with nonhazardous recyclable materials (NRMs) not addressed in other Department specifications. Applicable Department engineering specifications govern the evaluation of engineering factors associated with the NRM product.

The Department's goal is to use materials with environmental qualities that do not necessitate short-term or long-term management (i.e., worker protection, deed restrictions, tracking, monitoring, or special handling after the project life) in Department specification items.

The Department prohibits the use of hazardous wastes in Department projects; therefore, the Department will reject the use of those wastes as outlined in Item 6, "Control of Materials," Article 6.9, "Recyclable Materials," of the Department's *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges.*

Hazardous waste definitions are located in the Texas Administrative Code (TAC), 30 TAC 335.1. Refer to 30 TAC 335.504 to determine if a material is a hazardous waste.

11000.2. Definitions. This Specification references the following terms:

- *NRM*—nonhazardous recyclable material that has been recovered or diverted from the nonhazardous waste stream for the purpose of reuse or recycling in the manufacture of products that may otherwise be produced using raw or virgin materials.
- *NRM Product*—a road construction material that includes one or more NRMs. NRM products must not endanger human health, the environment, or the waters of the state. Refer to 30 TAC 335.4 and Section 26.121 of the Texas Water Code. The relevant Texas environmental statutes are located at http://www.sos.state.tx.us/tac. Since the potential for environmental harm depends on the final physical state in which the NRM resides, the environmental suitability will ultimately be determined for the product that contains the NRM, not the NRM itself. Examples of typical Department NRM products include concrete, hot mix, base, subgrade, embankment and backfill materials, landscaping materials, and metal applications that contain one or more NRMs.
- *Contractor*—entity responsible for meeting the requirements of the bid item in which an NRM product is a component. The Contractor may receive NRM products from producers, suppliers, agents, generators, and other Contractors, but is the entity who must assure that all the requirements of this Specification are met, including product approval, testing, certification, document flow, handling, control and retention, and compliance with applicable waste management and recycling regulations.
- *Supplier/Producer*—entity that first introduces the NRM product into a construction material or process. The Contractor may be the supplier/producer.

- *Chemical of Concern (COC)*—any chemical in a product that has the potential to adversely affect human health, the environment, or waters in the state, when applied to the land, due to its concentration, distribution, and mode of toxicity. COCs are identified after considering the originating sources and processes that generated the recycled materials used in an NRM product.

11000.3. Approval Criteria. The Department's decision regarding the use of an NRM product is dependent on two factors:

- Engineering—meets applicable department engineering specifications and other engineering evaluations deemed necessary by the Department
- Environmental—poses an acceptable level of potential environmental risk, following an evaluation of its environmental characteristics.

11000.4. NRM Product Approval Process.

A. Eligibility. To be eligible for use on Department projects, the NRM product must:

- meet all applicable Department engineering specifications and other engineering evaluations deemed necessary;
- contain only NRMs that meet the standards listed under Item 6, "Control of Materials," Article 6.9, "Recyclable Materials," of the *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges*;
- contain only NRMs that are managed and protected from loss, as would be raw materials, ingredients, or products;
- be used without the need for short-term or long-term management, such as special worker protection precautions, deed restrictions or notices (i.e., institutional control requirements associated with the reuse of contaminated media as discussed in 30 TAC 350.36), tracking, monitoring, special handling after the project life, or special engineering controls; and
- not present an increased risk to human health, the environment, or waters in the state when applied to the land or used in products that are applied to the land.

The NRM Product Eligibility Process chart illustrates the NRM product eligibility process.

The following NRMs have established histories of use in Department construction projects and are administered by other Department specifications:

- aluminum;
- compost;
- glass beads;
- ground granulated blast furnace slag;
- shredded brush;
- steel;
- tire rubber;

- ceramics, glass cullet, plastics, and crushed concrete from non-industrial sources;
- reclaimed asphalt pavement;
- fly and bottom ash from electrical utility plants; and
- Department-owned materials.

Products containing these established NRMs and meeting the first four criteria of Article 11000.4 may be presumed to meet the fifth criterion if they have not come into contact with any hazardous materials.

To demonstrate that other NRM products meet the fifth criterion of Article 11000.4, the concentrations of all COCs must meet the following requirements.

The concentrations in the product must be either:

- less than the COC concentrations found in the traditional material that is being replaced;
- equal to or below the corresponding “Texas-Specific Background Concentrations” as defined by the Texas Commission on Environmental Quality (TCEQ) in 30 TAC 350.51(m); or
- less than the Tier 1 “Residential Protective Concentration Levels” (PCLs) for combined exposure pathways ($^{Tot}Soil_{Comb}$), as defined in 30 TAC 350, when applying the general conservative assumptions for surface soil, Class 1 Groundwater, and a 30 acre source area.

The concentrations of all COCs must also meet one of the following requirements.

- The concentrations in the product must be either:
  - equal to or below the corresponding “Texas-Specific Background Concentrations” as defined by the TCEQ in 30 TAC 350.51(m); or
  - less than the Tier 1 “Groundwater Protective Soil PCLs” ($^{Tot}Soil_{Comb}$) as defined in 30 TAC 350, when applying the general conservative assumptions for surface soil, Class 1 Groundwater, and a 30 acre source area.

or

- the concentrations measured in the leachate following a scientifically valid synthetic leaching procedure performed on a sample of the product must be either:
  - less than the allowable PCLs for groundwater ingestion ($^{GW}GW_{Ing}$) as defined in 30 TAC 350 or
  - equal to or less than the leachate concentrations of the same COCs found in traditional materials, when comparing data using similar leachate testing methods. (Refer to the Table 1 for a partial listing of leachate COC concentrations identified in traditional materials. Use this table or other published and scientifically valid data with Department approval to demonstrate typical leachate concentrations in traditional construction materials, such as concrete, natural aggregates, bituminous materials, and others.)

NRM products that do not meet all of eligibility criteria may still be acceptable for use in Department projects. However, these materials must undergo additional analysis and testing necessary to demonstrate to the Department that they do not present an increased risk to human health, the environment, or waters in the state when applied to the land or used in products that are applied to the land. Contractors should coordinate with the Department's Environmental Affairs Division when seeking approval for such materials. The Department reserves the right to reject without cause any NRM product that does not meet all of the eligibility criteria.

B. Testing Protocol for Environmental Criteria. To demonstrate compliance with this Specification, suppliers/producers supplying recycled materials not listed in Article 11000.4 as having an established history of use in Department construction projects must:

- collect environmental testing data for every 10,000 tons of those materials delivered to the Department or
- establish an internal testing program that regularly measures and documents that those products meet the environmental criteria outlined in this Specification.

The sampling and analysis plan must be developed in accordance with standard industry practices, including Chapter 9 of the EPA's SW-846, "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods," Third (or latest) Edition. The Department reserves the right to verify compliance with these environmental specifications and may perform additional verification testing.

Suppliers/producers who choose to use an internal testing program must first submit a detailed description of the program to the Department for review and approval before the Department receives any material.

The description must include the following information:

- a description of the originating sources and process that generated the recycled materials used;
- if applicable, waste characterization data for the recycled materials used;
- rationale for including and/or excluding COCs in the testing program based on the originating sources and processes that generated the recycled materials used;
- methods used to track the incoming sources of recycled materials to ensure that the rationale for including and/or excluding COCs in the testing program remains valid;
- the sampling protocol;
- the sampling frequency and rational for the sampling frequency; and
- documentation procedures.

The Department reserves the right to periodically inspect documentation associated with the testing program. The schedule and frequency for the documentation inspections are at the Department's discretion. The Department also reserves the right to verify compliance with engineering and environmental specifications and may perform additional verification testing.

The Department may add NRM products to the Department's Material Producer List if the supplier/producer's testing program demonstrates a history of compliance with this Specification.

11000.5. NRM Product Certification. Contractors who intend to use any NRM products listed above under Article 11000.4 or those listed on the MPLs entitled "Nonhazardous Recyclable Materials" or "Recycled Asphalt Shingles" are not required to document the use of those materials.

Report other NRM products on Form CSTM-NRM-2. A single Form CSTM-NRM-2 can list several products that a company plans to supply for a given project. This form must be signed, certified, and sealed by a licensed professional engineer, and must have an attached copy of form CSTM-NRM-3 for each NRM from a supplier/producer certifying that the NRM meets all the environmental requirements of this Specification and states where that information can be reviewed.

11000.6. Document Requirements.

A. CSTM-NRM-2. Keep detailed documentation for the NRMs used in NRM products in the supplier/producer's files for ten calendar years, available for Department review. This documentation must include:

- documentation of the environmental sampling protocol,
- rationale for including and/or excluding COCs for environmental analyses, and
- analytical reports documenting that the COCs are at concentrations that meet the certification requirements.

B. CSTM-NRM-3. Keep detailed documentation for the NRMs used in NRM products in the supplier/producer's files for ten calendar years, available for Department review. This documentation must include:

- waste characterization data for the NRMs used,
- tracking methods for incoming sources of NRM used,
- copy of sampling protocol,
- rationale for including and/or excluding COCs for environmental analyses,
- analytical reports, including COCs and concentrations, and
- Material Safety Data Sheets (MSDS), if available, for the NRM.

11000.7. Compliance with Waste Management and Recycling Regulations Governed by Other Entities. The Department does not make environmental regulatory determinations for Contractors or material suppliers. Contractors must ensure that they comply with applicable Department specifications and relevant local, state, and federal regulations, regulatory guidance, laws, and statutes.

The Contractors and supplier/producer must ensure and certify that the generating sources of their NRM comply with waste management and recycling regulations when applicable. The only generating sources of NRMs currently suitable for recycling into Department projects are non-industrial, compost, petroleum-substance containing, or industrial.

A. Non-Industrial Generators. Non-industrial generators include schools, hospitals, churches, dry-cleaners, most service stations, and laboratories serving the public. Regulations for non-industrial generators are located in 30 TAC 330.

The recycling definition for non-industrial generators is expressed in 30 TAC 330.2 as: *Recycling — A process by which materials that have served their intended use or are scrapped, discarded, used, surplus, or obsolete are collected, separated, or processed and returned to use as a raw materials in the production of new products. Except for mixed municipal solid waste composting, that is, composting of the typical mixed solid waste stream generated by residential, commercial, and/or institutional sources, recycling includes the composting process if the compost material is put to beneficial use.*

B. Compost Generators. Regulations relevant to compost are located in 30 TAC 312 and 332. The Department allows the use of Class A biosolid compost.

C. Petroleum-Substance Containing Generators. Regulations relevant to petroleum-substance contaminated waste generators regulated by the TCEQ, plus environmental guidelines for reuse of certain petroleum-substance wastes in cold- and hot-mix paving applications, are located in 30 TAC 334.

Materials regulated by the Railroad Commission (RRC) in 16 TAC 1 must carry a permit from the RRC and meet Department's engineering and environmental criteria.

D. Industrial Generators. Industrial generators include power generation facilities, metal casters and other parts manufacturers, and laboratories serving an industry. Regulations relevant to industrial generators are located in 30 TAC 335.

Industrial generators that want to provide NRM products for Department projects must notify TCEQ of their intent to recycle, using TCEQ Form 0525, "Generator Notification Form For Recycling Hazardous or Industrial Waste," available at: http://www.TCEQ.state.tx.us.

11000.8. Leachate Concentrations for Traditional Construction Materials, (µg/L). To use this table, select the category for which the NRM product will be substituted. For example, a base product, including foundry sand as a fine aggregate, must not exceed the values shown in the aggregate column (in µg/L).

Table 1
Substitution Table

Metal	Aggregates	Cementitious Materials	Asphaltic Binders
Aluminum	24,000[1]	24,000[1]	24,000[1]
Antimony	13	6[1]	6[1]
Arsenic	10[1]	10[1]	10[1]
Barium	2,007	5,565	2,000[1]
Beryllium	4[1]	4[1]	4[1]
Cadmium	5[1]	5[1]	5[1]
Chromium	100[1]	162	100[1]
Cobalt	1,500[1]	1,500[1]	1,500[1]
Copper	1,300[1]	1,300[1]	1,300[1]
Lead	16	47	15[1]
Manganese	1,100[1]	1,100[1]	1,100[1]
Mercury	20	3	2[1]
Molybdenum	120[1]	237	120[1]
Nickel	490[1]	490[1]	490[1]
Selenium	50[1]	77	50[1]
Silver	120[1]	120[1]	120[1]
Thallium	2[1]	2[1]	2[1]
Vanadium	170[1]	287	170[1]
Zinc	7,300[1]	7,300[1]	7,300[1]

1. These numbers represent published risk-based values. Actual testing data resulted in lower levels.

In addition to these standards, conduct tests for other COCs if process knowledge indicates they may be present. Further, if the Contractor becomes aware of any other characteristics that could pose a hazard, the Contractor must reveal this data to Department.

11000.9. Archived Versions. Archived versions are available.

Exhibit 46.02

This exhibit was not previously submitted in November 2023

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Environmentally Sustainable Solutions to Recycle Oil Cuttings

Prof. Robert Gilbert

Prof. Amit Bhasin

Prof. Lynn Katz

Prof. Maria Juenger

Prof. Chadi El Mohtar

Darren Hazlett

Chih-Yu Tung

Jae Kyeong Jang

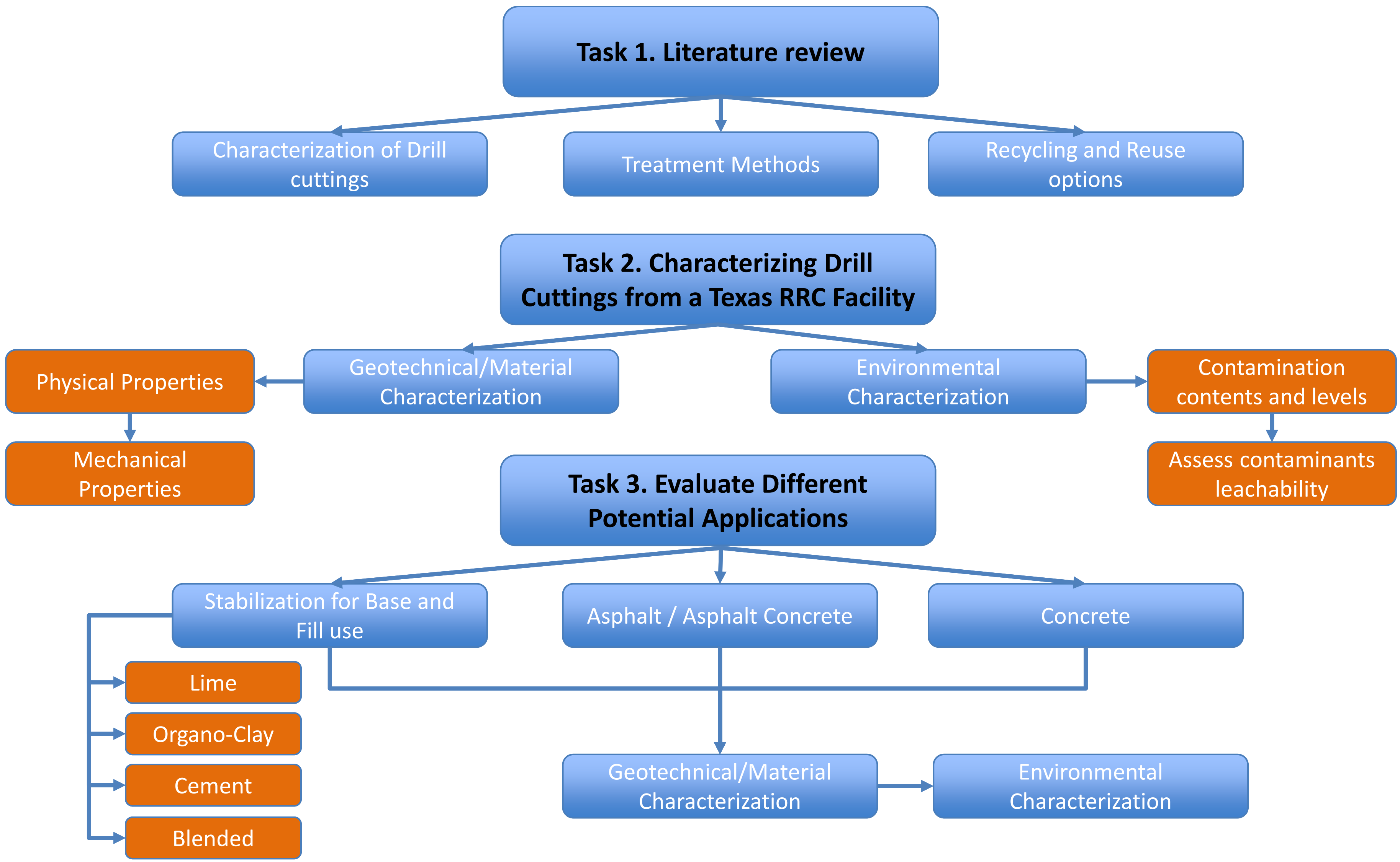
Karen Mena Arango

Introduction

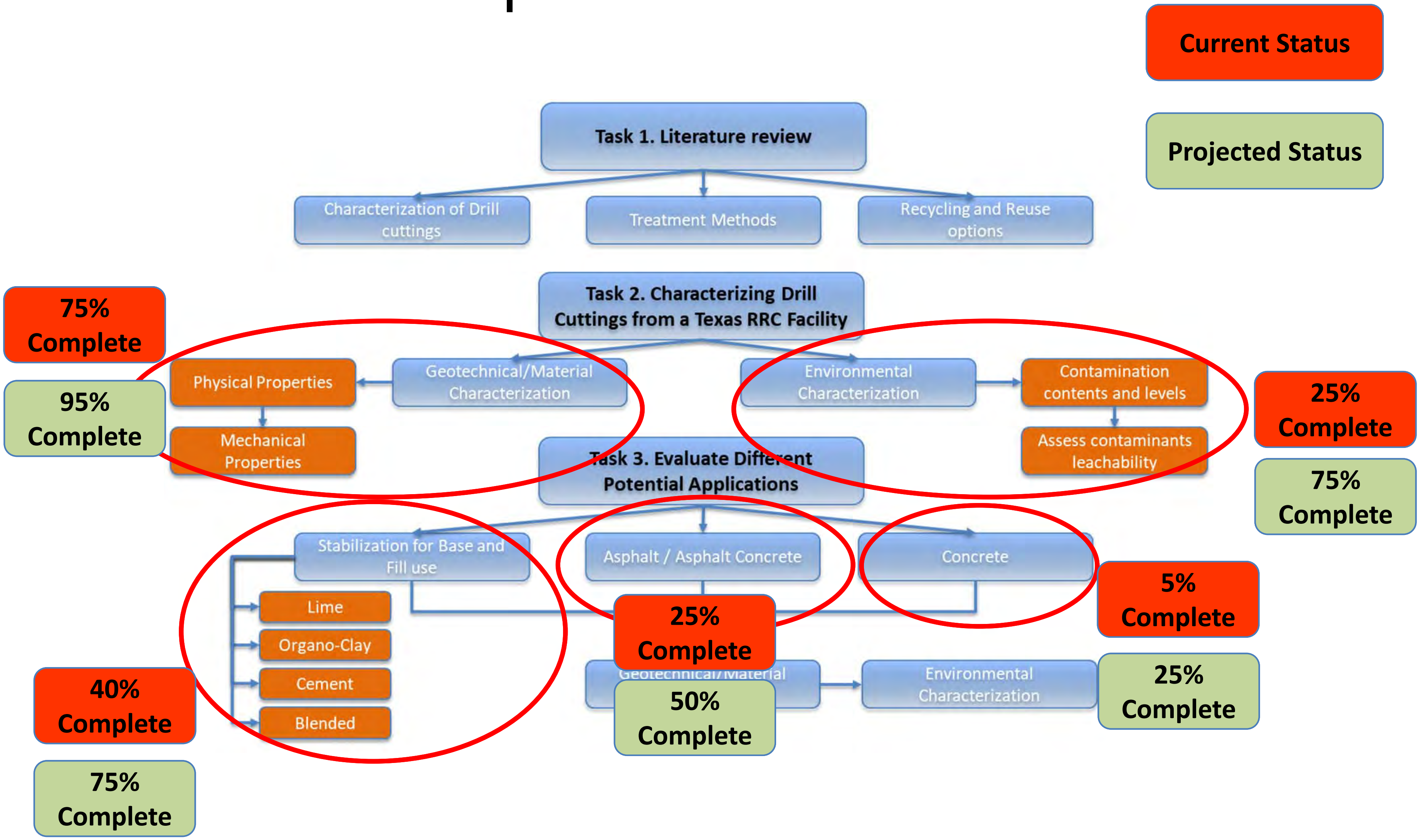
- Drill cuttings and spent drilling fluids are the major drilling wastes generated in greatest volumes during well installation
- In Texas, oil field drill cuttings are stockpiled at multiple locations throughout the state.
- These drill cuttings have amassed to millions of cubic yards and pose environmental risks due to presence of various potential contaminants:
  - Metals
  - Benzene, toluene, ethyl benzene, and xylene (BTEX)
  - Polycyclic aromatic hydrocarbons (PAHs)
  - Naphthalene, phenanthrene, and dibenzothiophene (NPD)
  - Naturally occurring radioactive materials (NORM)
  - Potential carcinogens and mutagens

Water surrounding drill cutting pile

Work Plan


Task 1. Literature review
Characterization of Drill cuttings
Treatment Methods
Recycling and Reuse options
Task 2. Characterizing Drill Cuttings from a Texas RRC Facility
Physical Properties
Geotechnical/Material Characterization
Environmental Characterization
Contamination contents and levels
Mechanical Properties
Assess contaminants leachability
Task 3. Evaluate Different Potential Applications
Stabilization for Base and Fill use
Asphalt / Asphalt Concrete
Concrete
Lime
Organo-Clay
Cement
Blended
Geotechnical/Material Characterization
Environmental Characterization

Last Update March 2023



Material Characterization

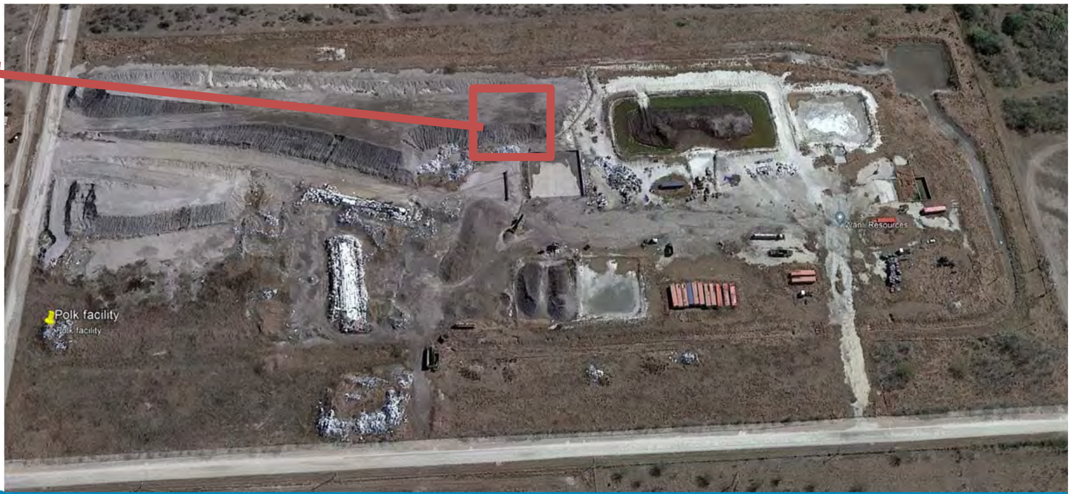
POLK FACILITY

Polk Facility

- Polk site (Near Falls City)
  - Mostly untreated cuttings
  - Small treated stockpile!!

Polk Facility

- Initial site visit (June 29th, 2022)
  - Walked facility
  - Obtained small samples for initial characterization



Polk **Facility**

- Second site visit (July 22nd, 2022)
  - Obtained 30 5-gallon buckets
  - Homogenized in the lab

Polk Facility

RAW MATERIAL CHARACTERIZATION

Raw Material Characterization

Geotechnical Testing	Environmental Testing
Water Content	Ignition Testing
pH	X-ray Fluorescence
Specific Gravity	X-ray Diffraction
Atterberg Limits	Thermogravimetric Analysis
Particle Size Distribution	Leaching Testing
Compaction	Total Organic Content
Unconfined Compression Strength	ICP-MS
	SVOCs / VOCs
	Chloride Concentration
	Total Petroleum Hydrocarbons

Geotechnical/Material Characterization

- Dark gray with a strong smell of petroleum
  - Larger clumps crumble with some pressure
- Initial water content: 21.2%

- Specific gravity: 2.63

Trial	1	2	3	Average
Specific Gravity	2.62	2.62	2.64	2.63

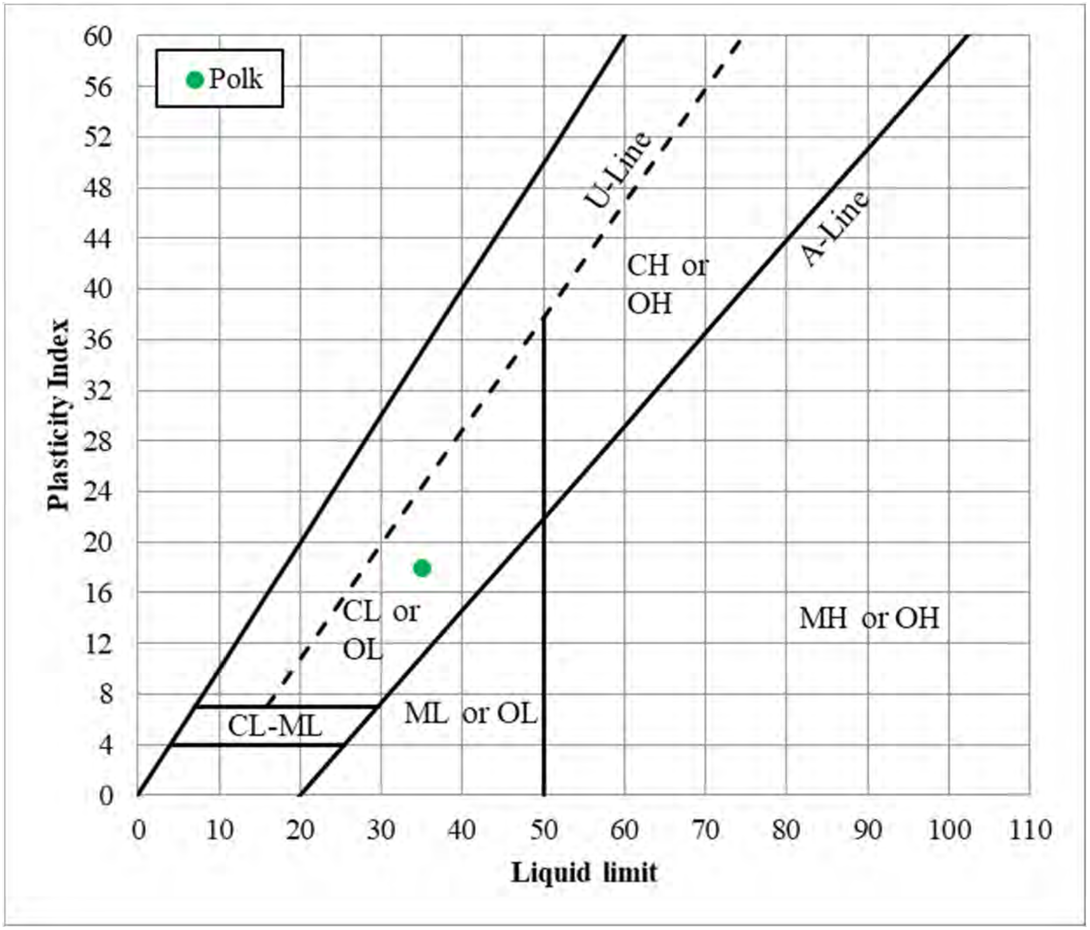
- Soil pH: 7.6

Trial	1	2	Average
pH	7.57	7.69	7.63
Temperature (°C)	24.4	24.6	24.5

Geotechnical/Material Characterization

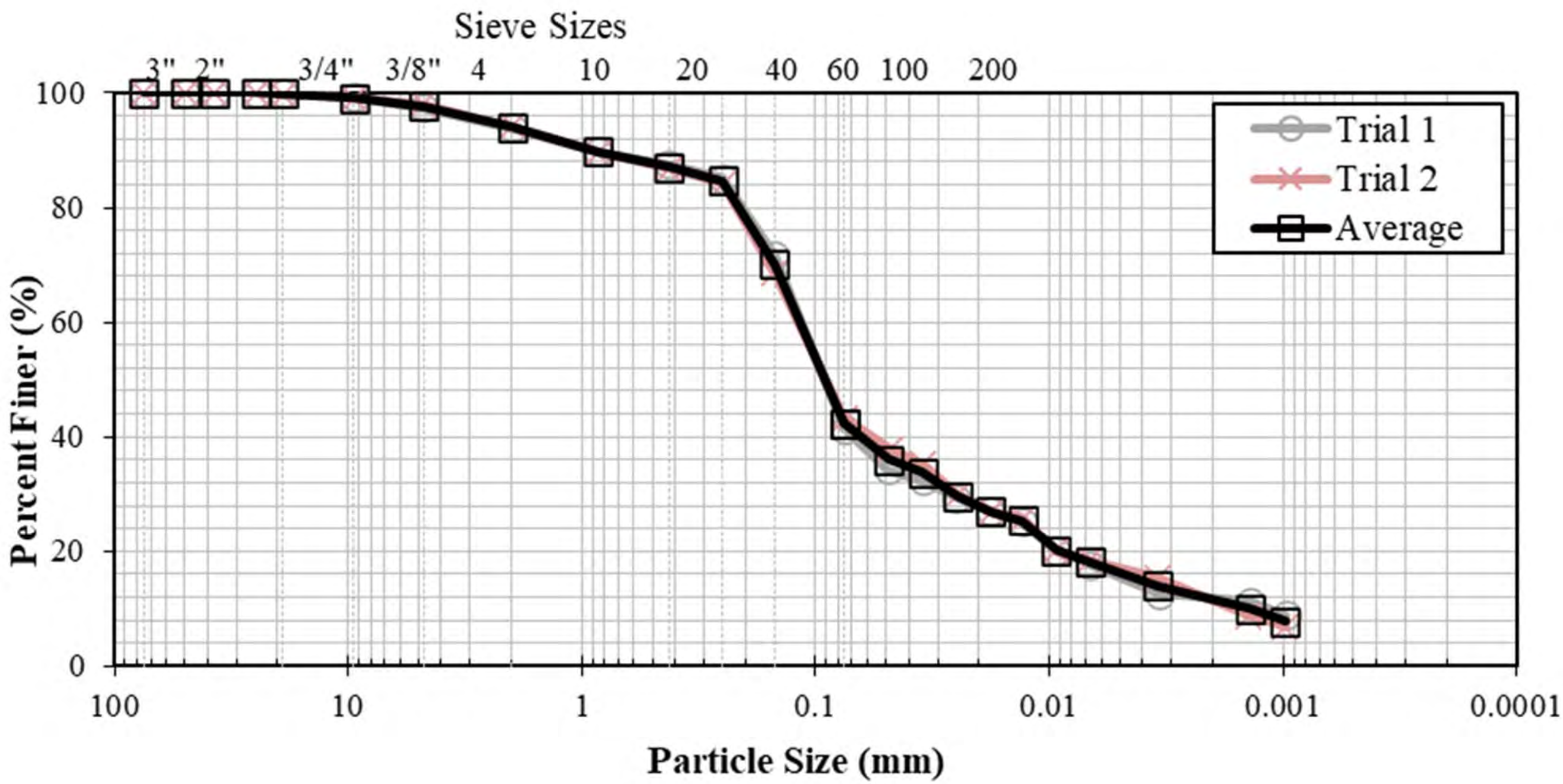
- Atterberg limits:

Trial	1	2	Average
LL(%)	34	35	35
PL(%)	16	17	17
PI(%)	18	18	18



Geotechnical/Material Characterization

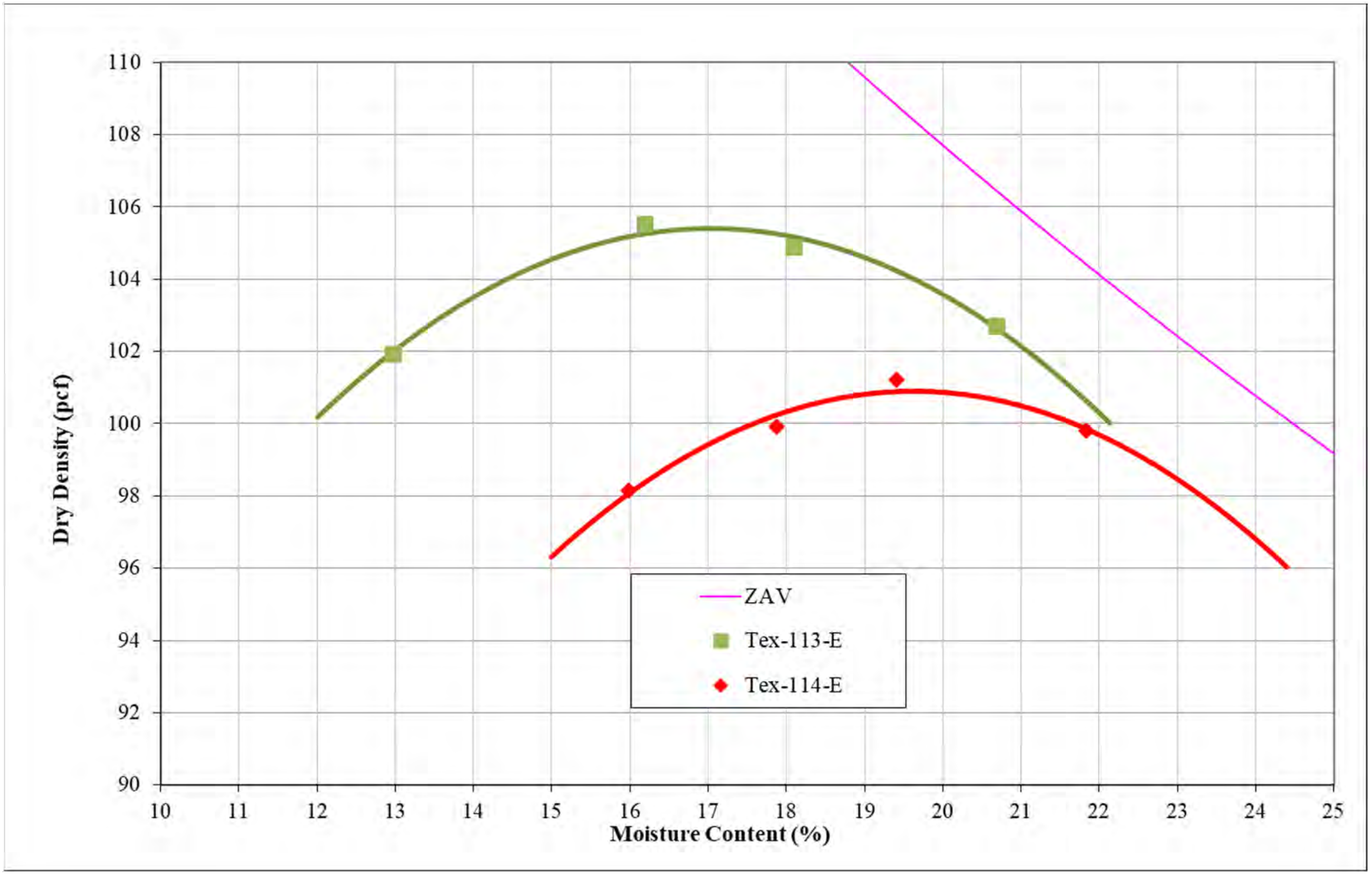
- Soil classification:
  - Clayey sand (SC)



Geotechnical/Material Characterization

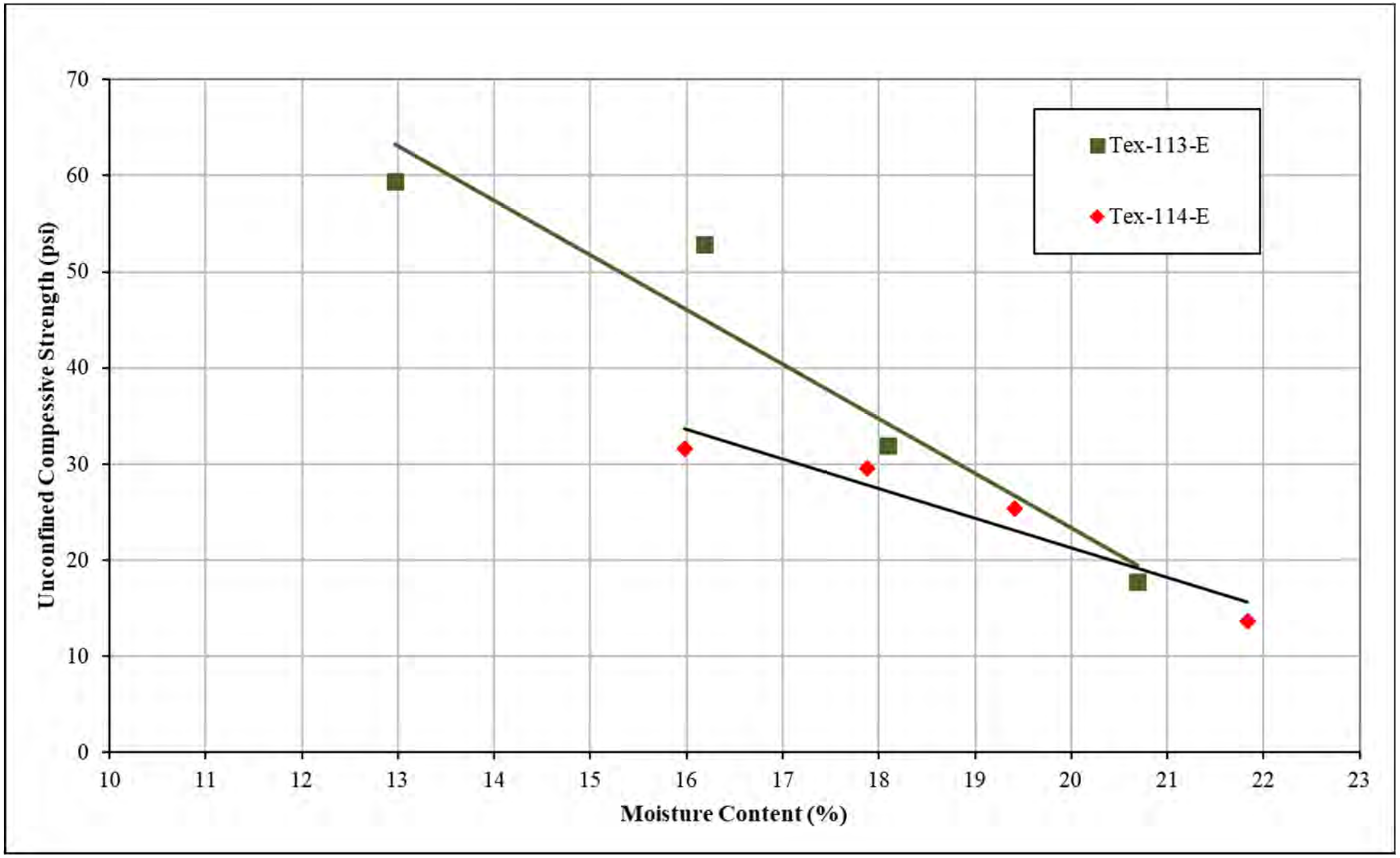
- Proctor Results

	Tex-113-E	Tex-114-E
Maximum Dry Density (pcf)	105.4	100.9
Optimum Water Content (%)	17.0	19.6



Geotechnical/Material Characterization

- Unconfined Compression for Tex-114-E and Tex-113-E



Environmental Characterization

- Moisture Content and Loss of Ignition

Material	Moisture Content (%)	LOI (%)
AA1010	26.4 ± 0.82	13.4 ± 0.27
AA1011	30.5 ± 0.75	15.6 ± 0.18
Polk	27.3 ± 0.91	9.6 ± 0.14

- Total Organic Carbon

Material	NPOC (ppm)	pH
P-1	19.61 ± 0.090	7.82 ± 0.03
P-2	17.53 ± 0.222	7.83 ± 0.03

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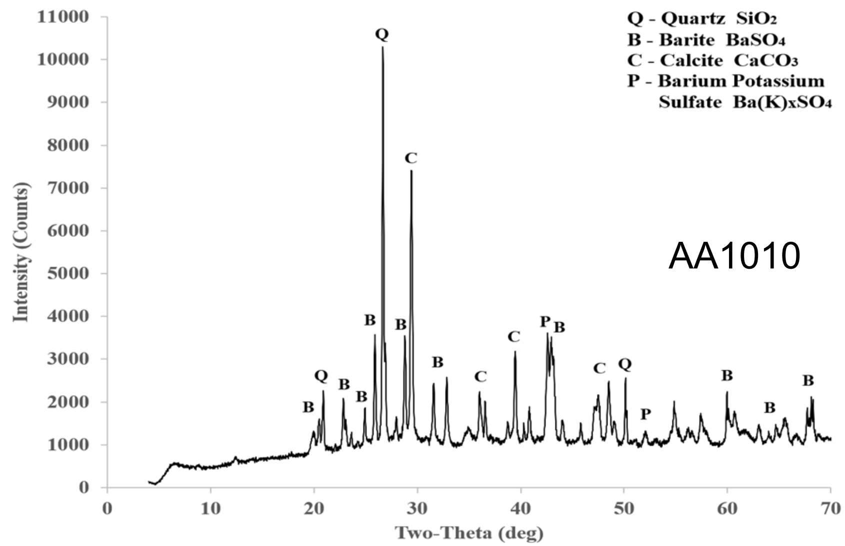
Environmental Characterization

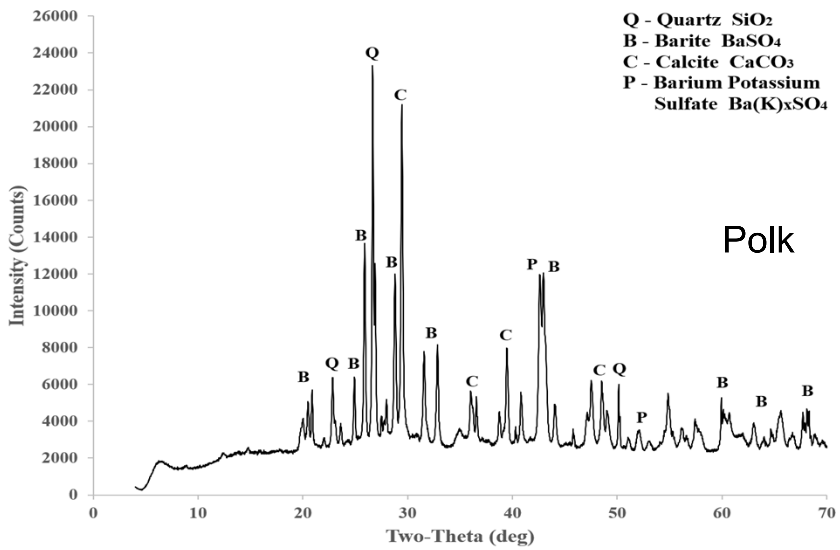
- Oxide Composition

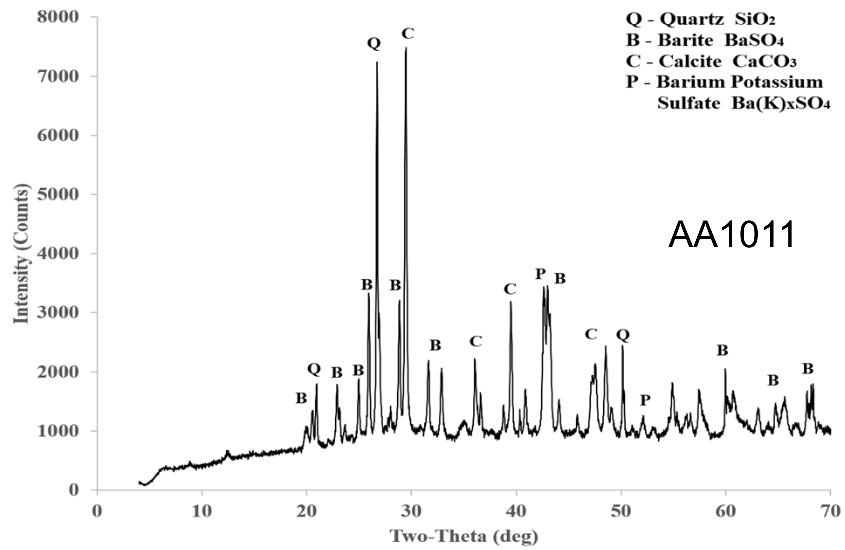
Component	Mass %		
	AA1010	AA1011	Polk
Na_2O	0.6936	0.6177	0.8398
MgO	1.6250	1.5481	1.4697
Al_2O_3	12.5229	11.5336	11.5329
SiO_2	41.4785	38.0155	42.6109
P_2O_5	0.2040	0.2123	0.1667
SO_3	4.8261	5.2476	7.9659
Cl	0.2176	0.1334	0.1922
K_2O	1.6665	0.5549	1.6243
CaO	20.8779	24.9648	17.4801
TiO_2	0.5276	0.4929	0.3997
Cr_2O_3	0.0232	0.0000	0.0187
MnO	0.0912	0.0767	0.0511
Fe_2O_3	4.8912	4.7305	3.1644
NiO	0.0070	0.0104	0.008
CuO	0.0261	0.0270	0.0167
ZnO	0.0305	0.0333	0.014
Br	0.0023	0.0000	0.0037
Rb_2O	0.0067	0.0059	0.0087
SrO	0.4301	0.5169	0.4972
Y_2O_3	0.0000	0.0000	0.0000
ZrO_2	0.0041	0.0000	0.0079
I	0.0345	0.0299	-
BaO	9.7860	10.2223	11.9156
PbO	0.0266	0.0263	0.0121

Environmental Characterization

- Qualitative Phase Analysis
  - Identified crystalline phases:
    - Quartz, SiO_2
    - Barite, $BaSO_4$
    - Calcite, $CaCO_3$
    - Barium Potassium Sulfate, $Ba(K)_xSO_4$



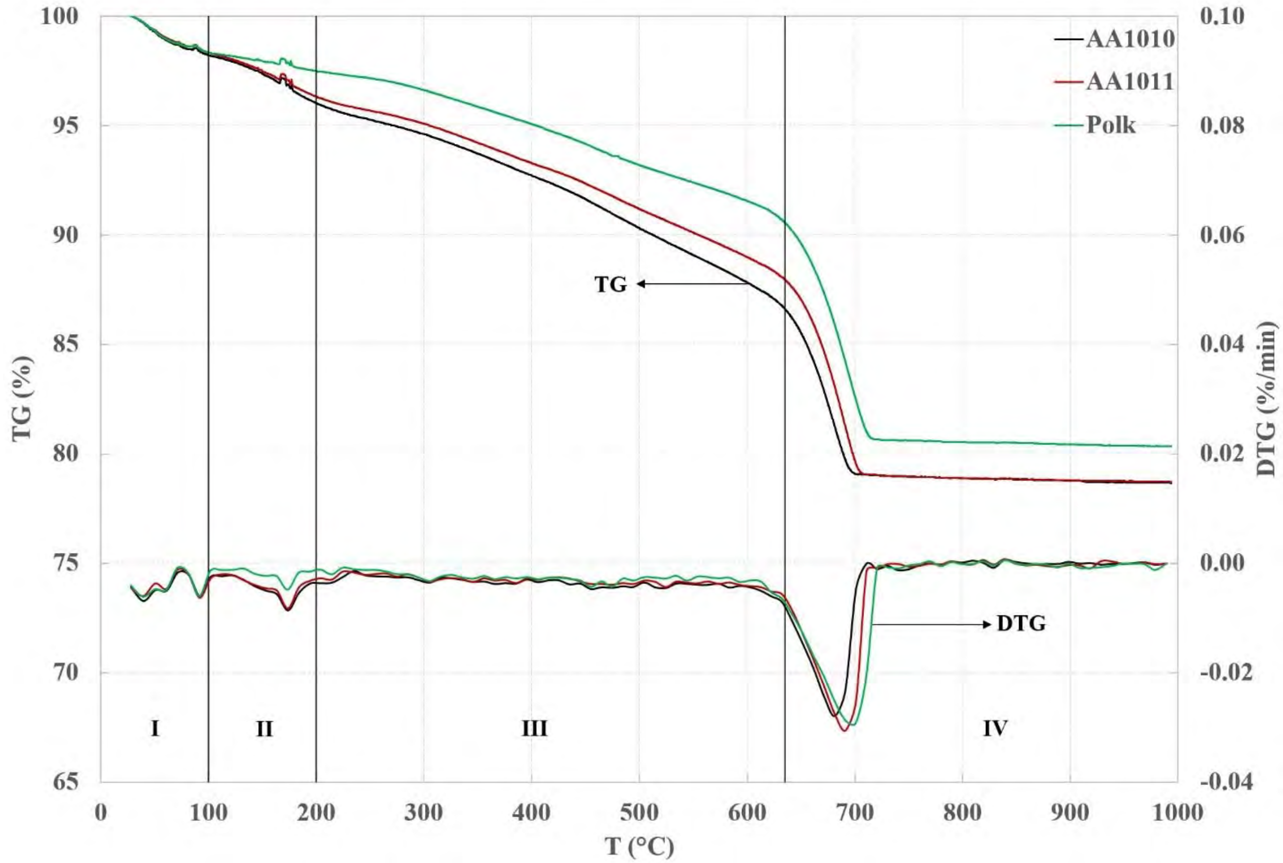




Environmental Characterization

- Thermogravimetric Analysis

- Stage I
  Loss of absorbed moisture
- Stage II
  Desorption of adsorbed water
- Stage III
  Thermal decomposition of organic matter
- Stage IV
  Decomposition of organic matte and the dehydroxylation of clay minerals, or decomposition of calcite



TGA results of drill cuttings collected using nitrogen purge gas. Data were collected using a Mettler-Toledo TGA/DSC 1, 50 mL/min of N_2 and a heating rate of 10 °C/min.

Environmental Characterization

- Trace Metal Concentrations

- Microwave digested drill cuttings (EPA Method 3050B)
- ICP-MS (Standard Method 3125)
- Trace metal grade nitric acid was used for dilution and sample preparation

Element	AA1010	AA1011	Polk
Li	382	304	345
Na	61600	27300	23600
Mg	14200	23800	19700
Al	30800	65400	51800
K	15600	17600	16100
Ca	30600	56900	44900
Cr	1150	112	403
Fe	51200	98800	96800
Co	20.1	34.1	32.4
Ni	286	150	1430
Cu	332	386	483
Zn	3750	1570	1640
As	75.7	102	124
Se	20.4	16.8	17.7
Sr	9810	9460	7790
Cd	5.81	5.94	5.81
Ba	75100	79700	85700
Pb	181	501	553

Environmental Characterization

- Semivolatile Organic Compounds
  - EPA Method 8270E
  - Gas Chromatography / Mass Spectrometry (GC-MS)
  - SVOCs included, but not limited to, the 16 priority-pollutant PAHs
  - Polk-u1- not homogenized
  - Polk-h2 and Polk-h3 - homogenized stockpile

Detection Summary

Material	Analyte	Result	Qualifier	RL	MDL	Unit	Dil Fac	Method
Polk-u1	Pyrene	0.0387	J	0.167	0.0146	ppm	1	8270E
Polk-h2	Pyrene	0.213	J	1.66	0.146	ppm	10	8270E
Polk-h3	Pyrene	0.228	J	1.66	0.146	ppm	10	8270E
LRA	No detections							
RAP	No detections							

RL: Reporting Limit, MDL: Method Detection Limit, Dil Fac: Dilution Factor
J: result is less than the RL but greater than or equal to the MDL and the concentration is an approximate value

Environmental Characterization

- Volatile Organic Compounds
  - EPA Method 8260D
  - Gas Chromatography / Mass Spectrometry (GC-MS)
  - Analytes included, but not limited to, benzene, toluene, ethylbenzene, xylene, and vinyl chloride

Detection Summary

Material	Analyte	Result	Qualifier	RL	MDL	Unit	Dil Fac	Method
Drill Cuttings-1	Xyelens, Total	0.000458	J	0.00109	0.000235	mg/kg	1	8260D
	m,p-Xylenes	0.000458	J	0.00109	0.000235	mg/kg	1	8260D
Drill Cuttings-2	Xyelens, Total	0.000298	J	0.00101	0.000219	mg/kg	1	8260D
	m,p-Xylenes	0.000298	J	0.00101	0.000219	mg/kg	1	8260D
Drill Cuttings-3	Xyelens, Total	0.000458	J	0.00104	0.000224	mg/kg	1	8260D
	m,p-Xylenes	0.000458	J	0.00104	0.000224	mg/kg	1	8260D

RL: Reporting Limit, MDL: Method Detection Limit, Dil Fac: Dilution Factor
J: result is less than the RL but greater than or equal to the MDL and the concentration is an approximate value

Material Performance after Treatment

STABILIZATION FOR FILL APPLICATIONS

Stabilization for Fill Applications

- Potential treatments
  - Hydrated lime
  - Organoclay
  - Cement

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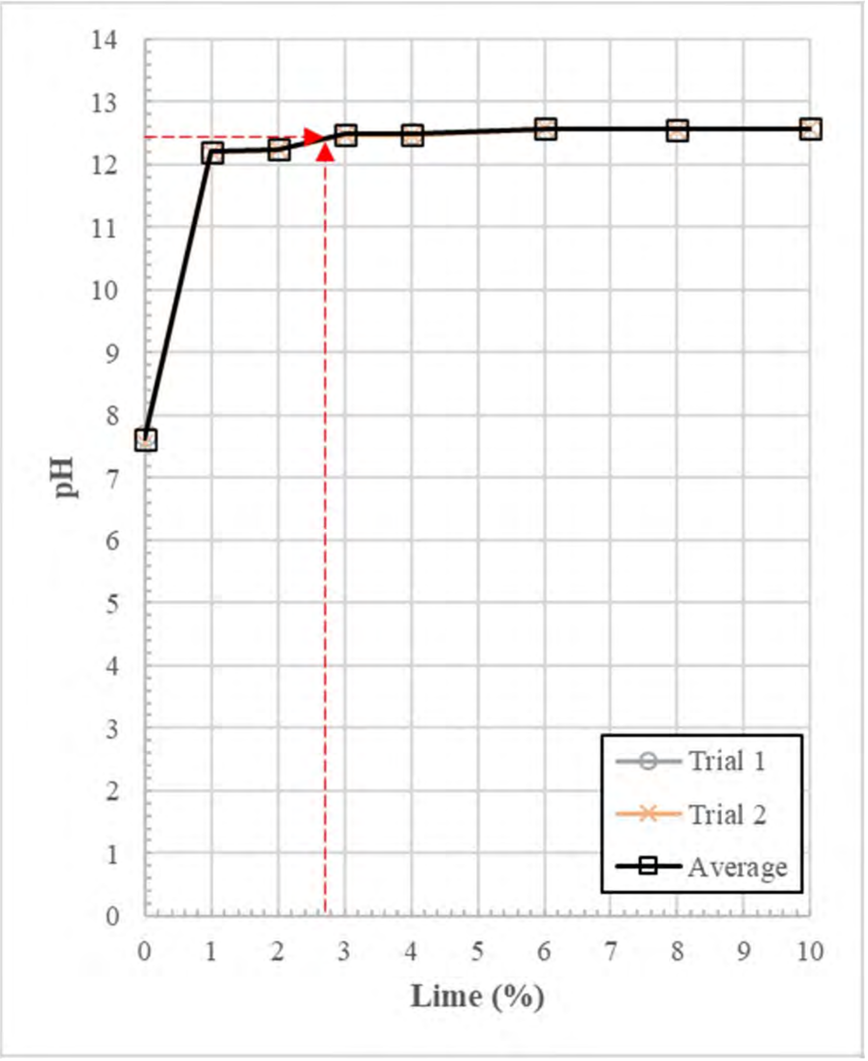
Stabilization with Admixtures-Lime

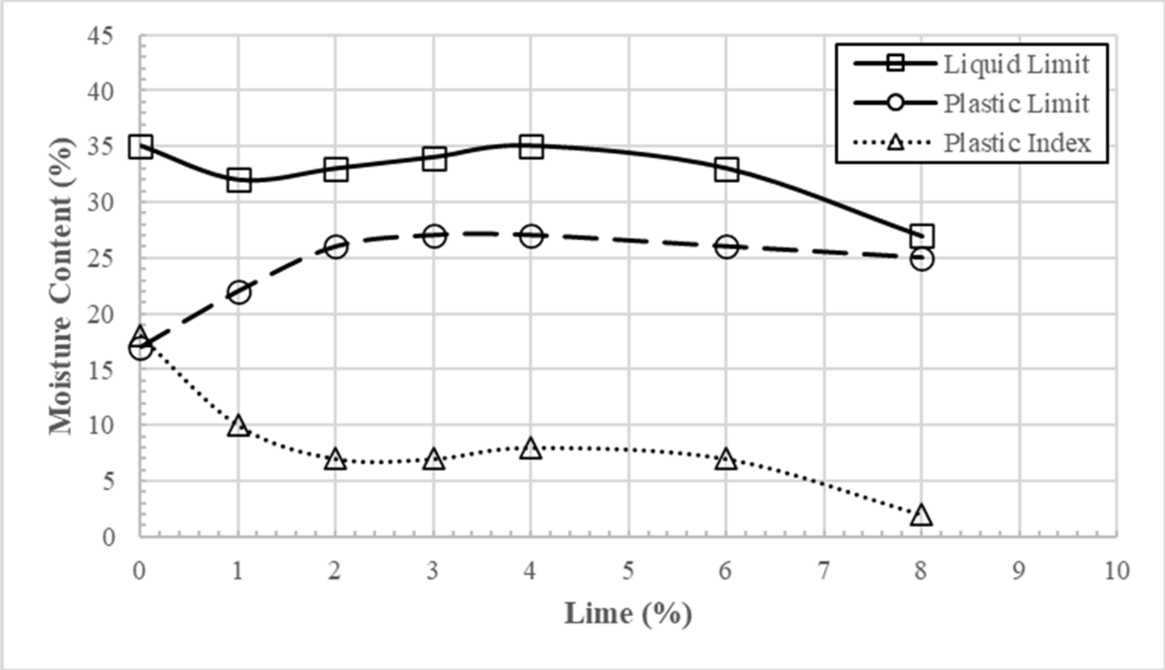
- Soil-lime pH:
  - Recommended: 2.7%

Lime (%)	pH	Temp (°C):
0	7.63	24.5
1	12.21	24.9
2	12.24	24.6
3	12.49	24.9
4	12.49	24.9
6	12.57	23.7
8	12.56	24.3
10	12.57	24.1



Stabilization with Admixtures-Lime

- Soil-lime Atterberg:

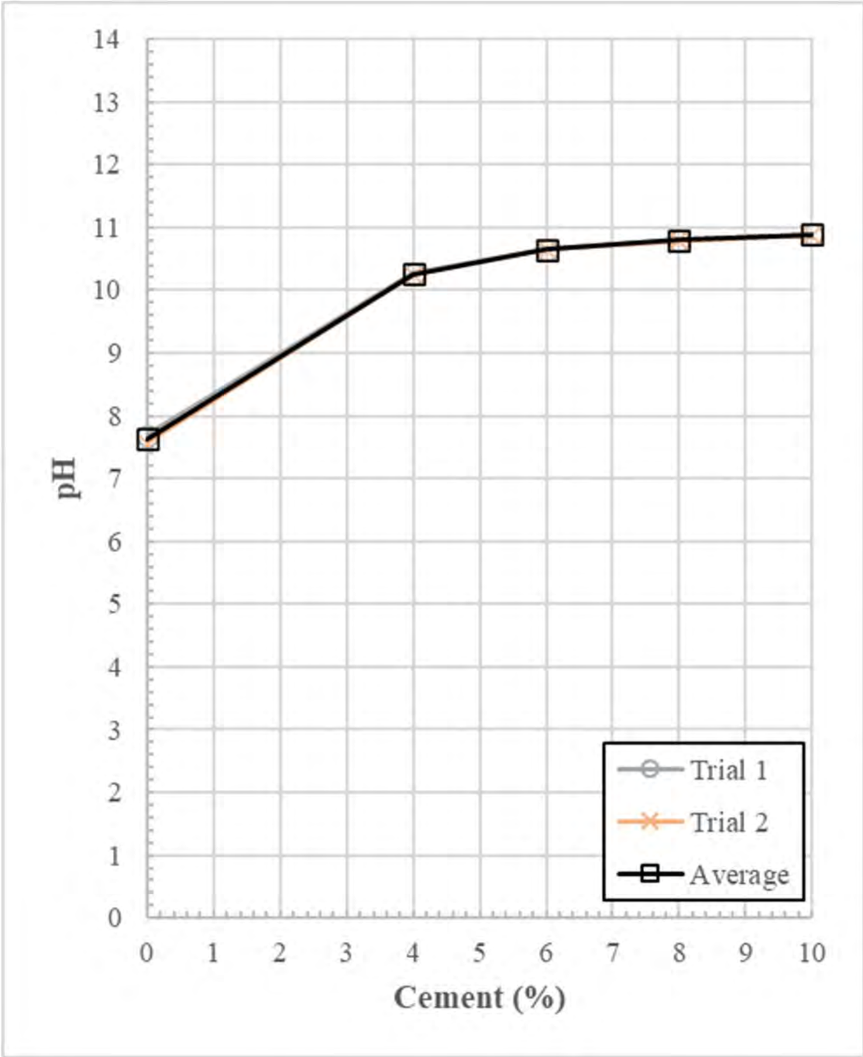


Lime (%)	0	1	2	3	4	6	8
Liquid Limit (%)	35	32	33	34	35	33	27
Plastic Limit (%)	17	22	26	27	27	26	25
Plastic Index (%)	18	10	7	7	8	7	2

Stabilization with Admixtures-Cement

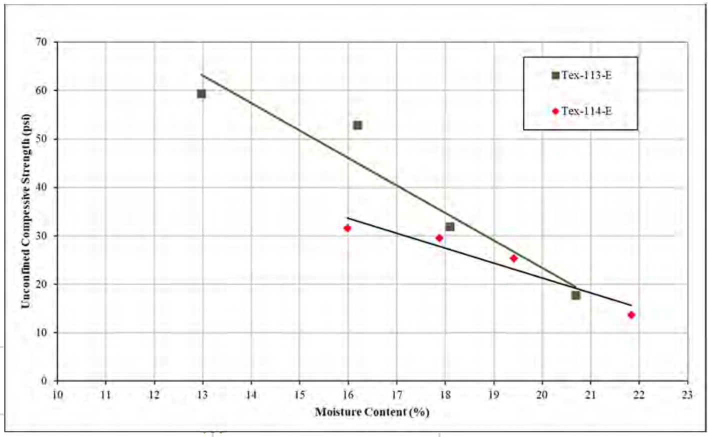
- Soil-cement pH:

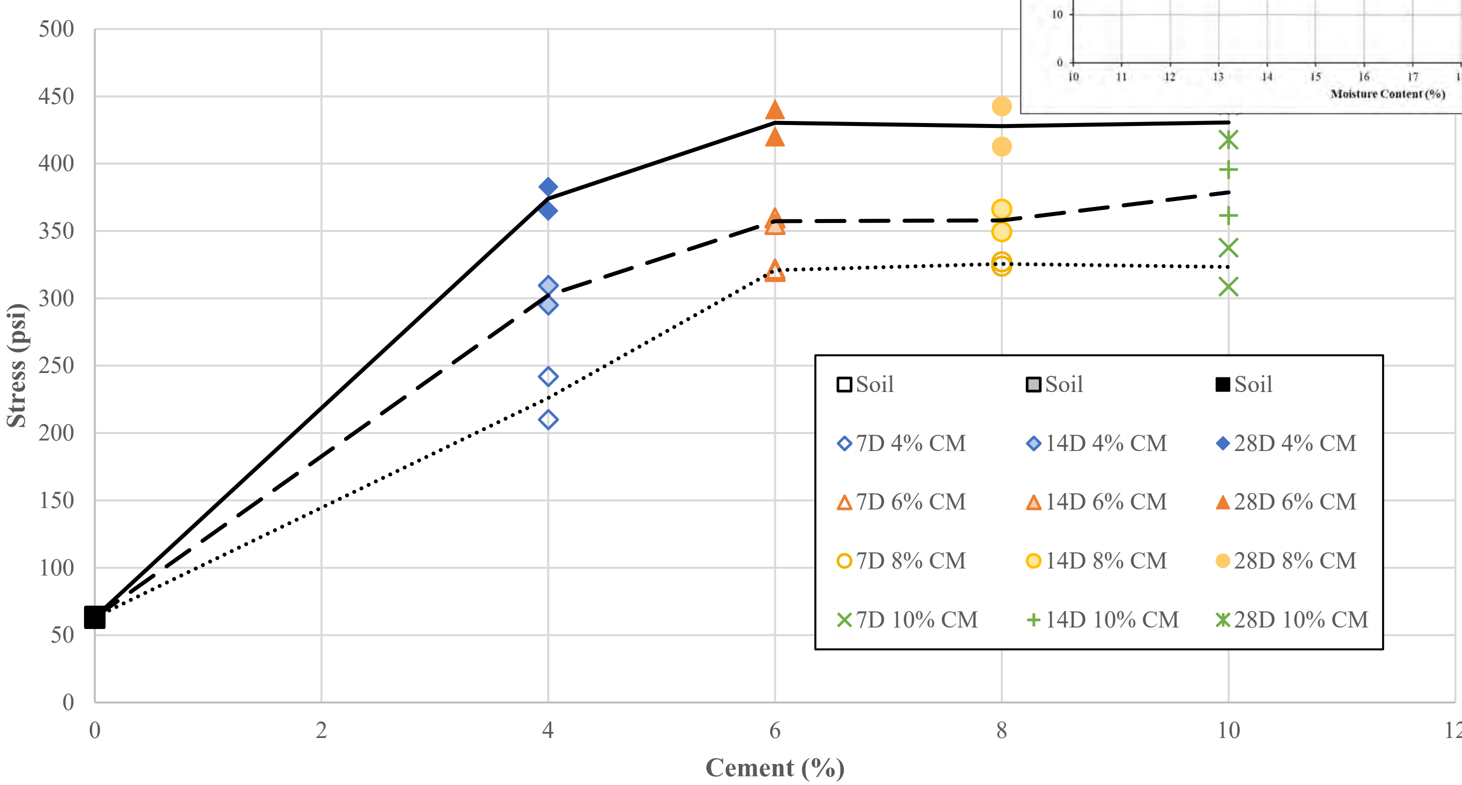
Cement (%)	pH	Temp (°C):
0	7.63	24.7
4	10.26	24.7
6	10.65	24.7
8	10.80	24.7
10	10.89	24.7



Stabilization with Admixtures-Cement

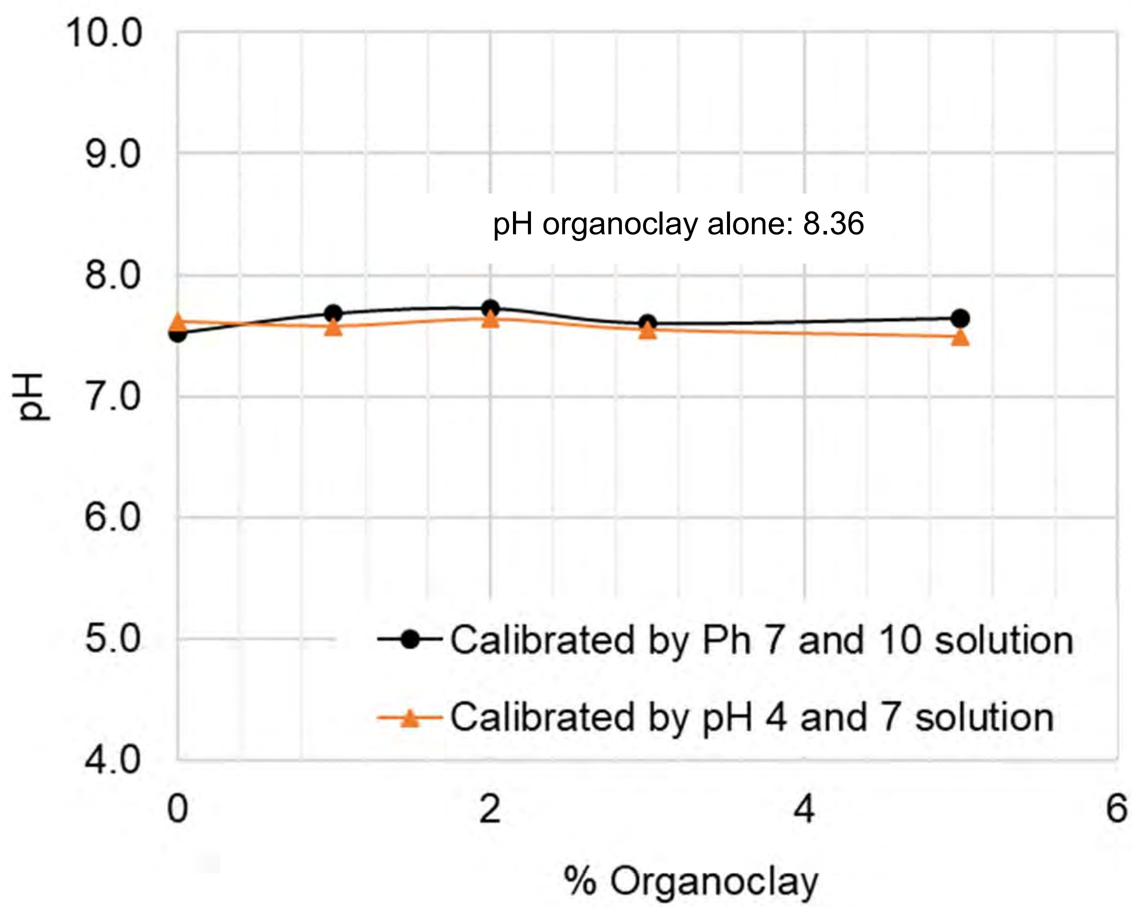
- Soil-cement Strength:





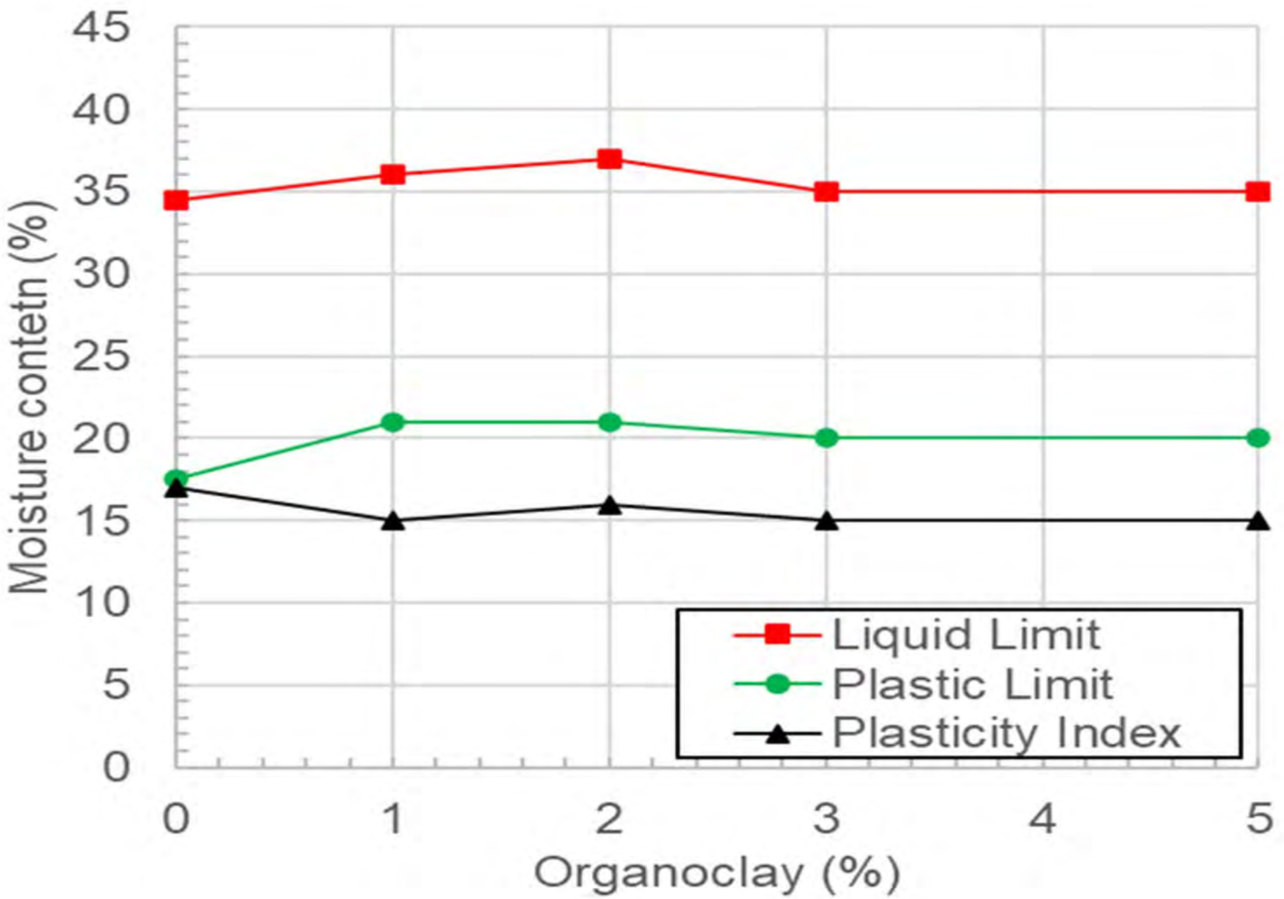
Stabilization with Admixtures-Organoclay

- Soil-OrganoClay pH:



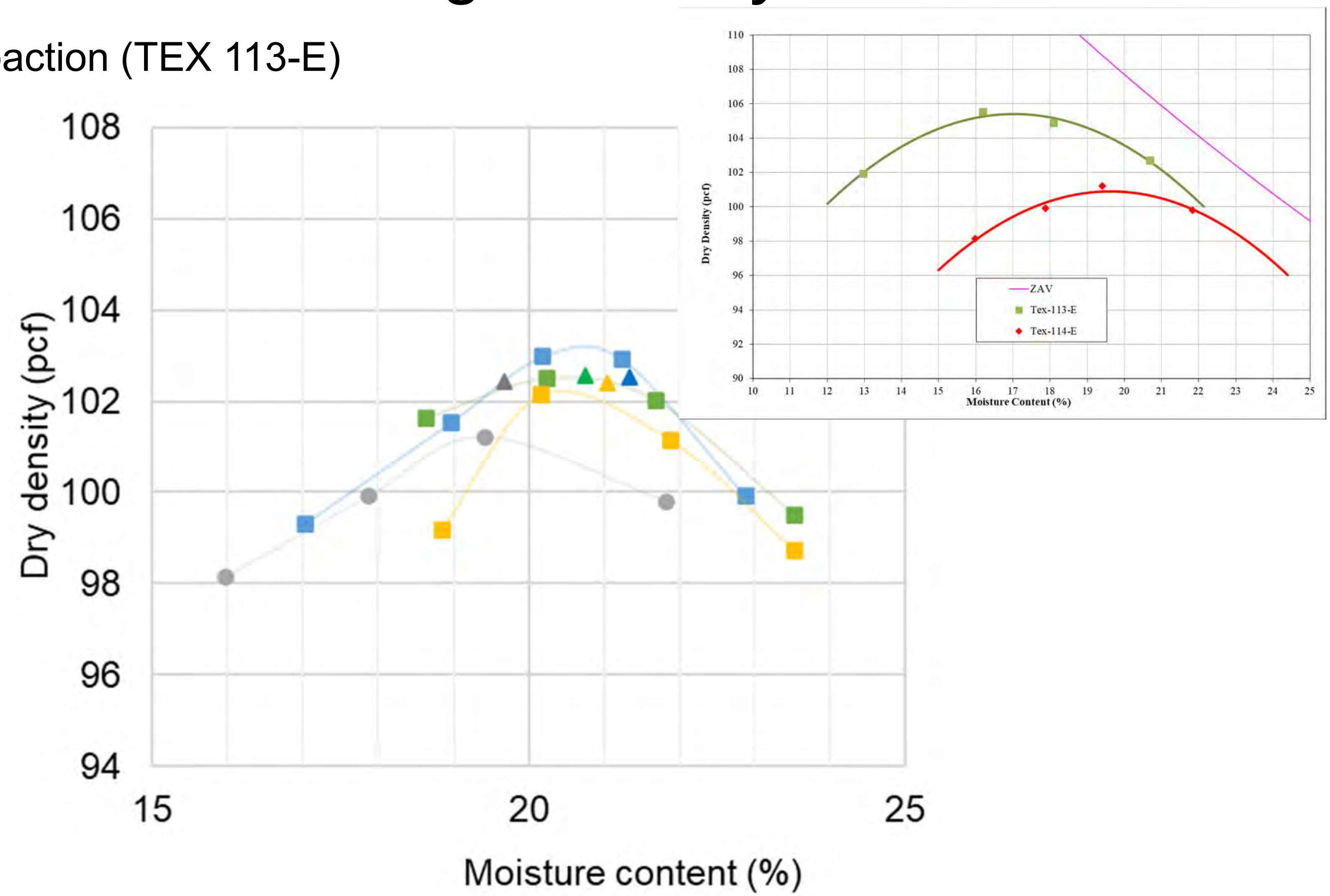
Stabilization with Admixtures- Organoclay

- Atterberg Limits



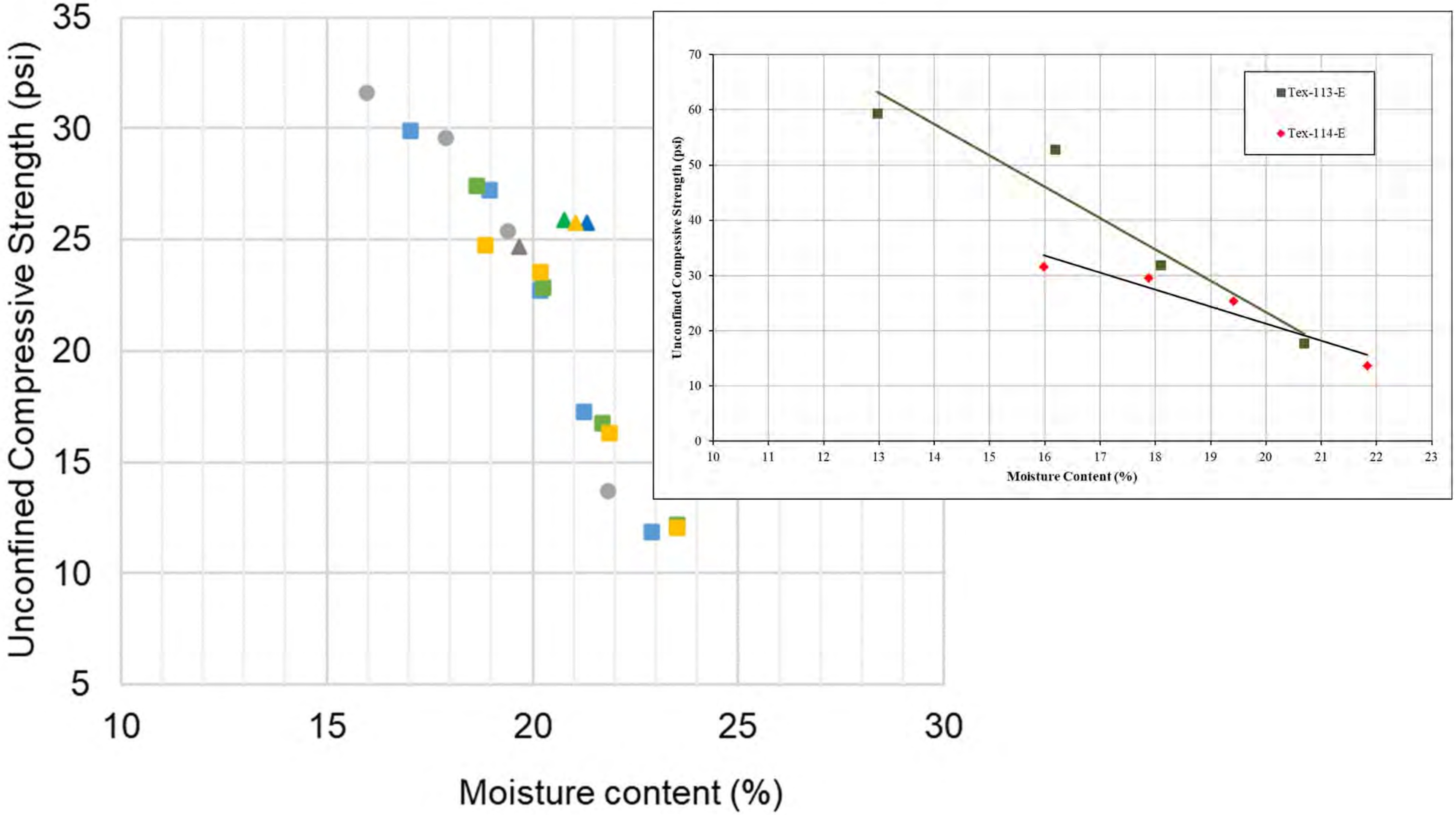
Stabilization with Admixtures-Organoclay

- Compaction (TEX 113-E)



Stabilization with Admixtures- Organoclay

- Unconfined Compressive Strength tests



Stabilization with Admixtures-Summary

- Lime:
  - Lime treatment may not work well
  - pH curve is not a gradual increase like typically seen
  - Low Plastic Index (may not enough clay minerals to provide aluminum to the reaction)

- Cement
  - Adding Cement can help increase strength of drill cuttings
  - Strength can be increased 7 times, from 60 psi to 420 psi.
  - Adding 6% cement to the drill cuttings is the optimal dosage from strength enhancement.

- OrganoClay
  - no obvious impact to the physical properties of drill cuttings

Material Performance after Treatment

STABILIZATION FOR BASE APPLICATIONS

Base Materials

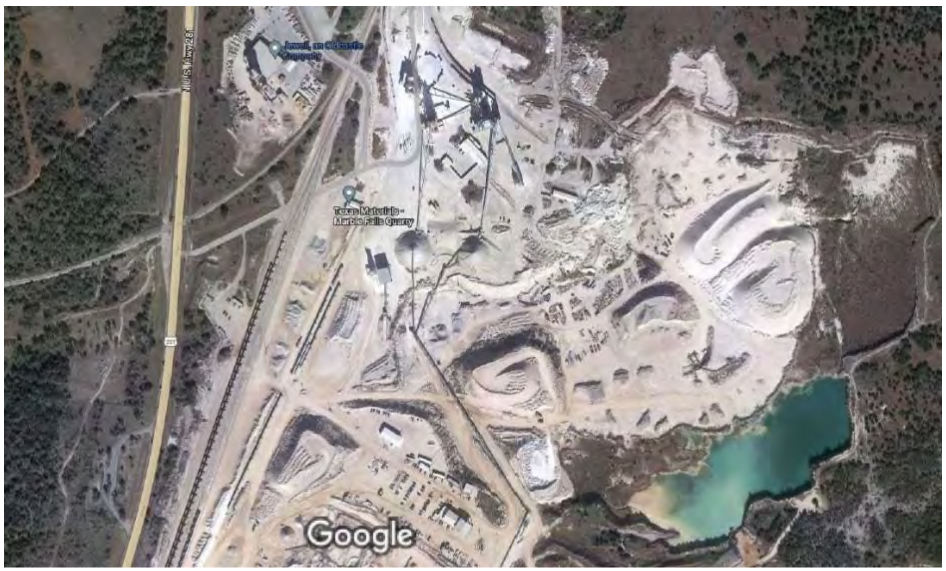
- TxDOT Item 247: Flexible Base

Property	Test Method	Grade 1–2	Grade 3	Grade 4[2]	Grade 5
Sampling	Tex-400-A				
Master gradation sieve size (cumulative % retained)	Tex-110-E				
2-1/2"		0	0	As shown on the plans	0
1-3/4"		0–10	0–10		0–5
7/8"		10–35	–		10–35
3/8"		30–65	–		35–65
#4		45–75	45–75		45–75
#40		65–90	50–85		70–90
Liquid Limit, % Max	Tex-104-E	40	40	As shown on the plans	35
Plasticity Index, Max[1]	Tex-106-E	10	12	As shown on the plans	10
Plasticity index, Min[1]		As shown on the plans	As shown on the plans	As shown on the plans	As shown on the plans
Wet ball mill, % Max	Tex-116-E	40	–	As shown on the plans	40
Wet ball mill, % Max increase passing the #40 sieve		20	–	As shown on the plans	20
Min compressive strength, psi	Tex-117-E			As shown on the plans	
lateral pressure 0 psi		35	–		–
lateral pressure 3 psi		–	–		90
lateral pressure 15 psi		175	–		175

1. Determine plastic index in accordance with Tex-107-E (linear shrinkage) when liquid limit is unattainable as defined in Tex-104-E.
2. Grade 4 may be further designated as Grade 4A, Grade 4B, etc.

Raw Base Course Materials

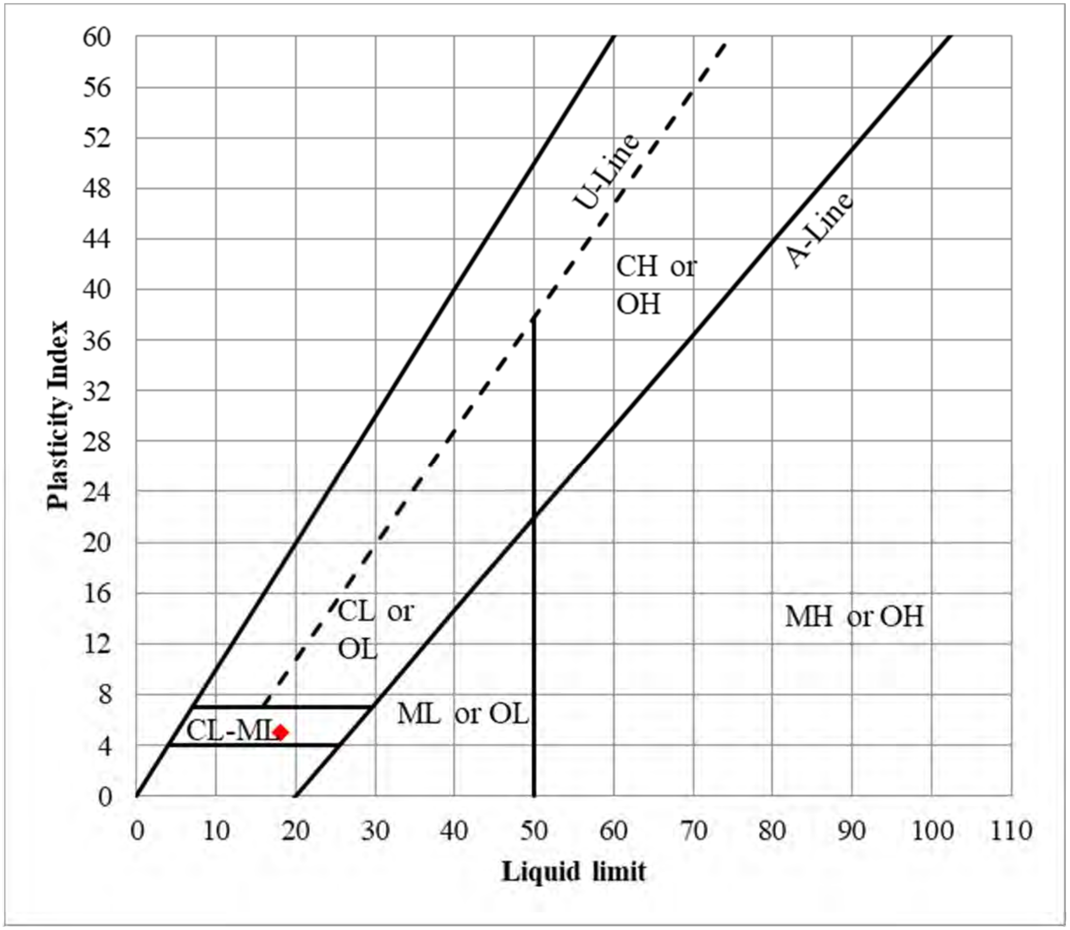
- Marble Falls Site
  - Reddish tan
    - Hard clumps cant be easily broken
  - Initial water content: 3.0%
  - Base course material for roadway construction
  - Blend with drill cuttings



Raw Base Course Materials

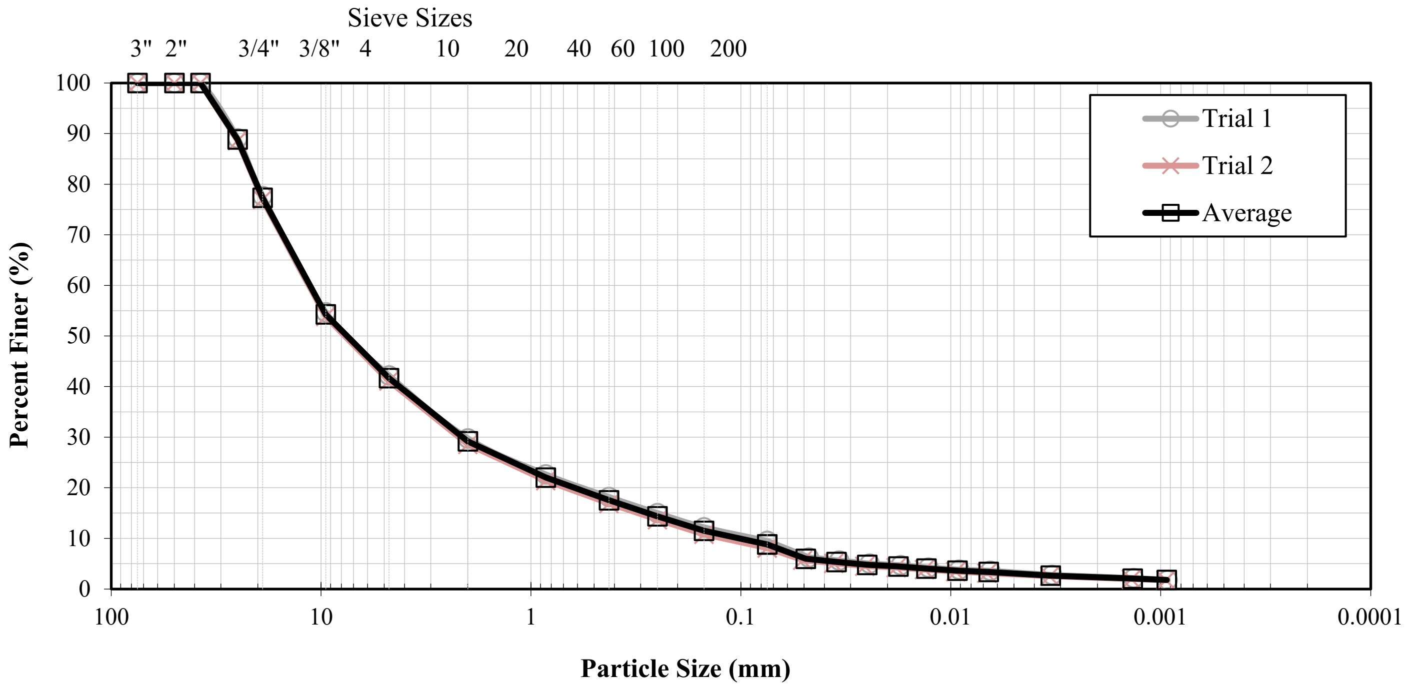
- Atterberg limits:

Liquid Limit (%)	18
Plastic Limit (%)	13
Plastic Index (%)	5



Raw Base Course Materials

- Soil classification:
  - Well-graded gravel with silt (GW-GM)

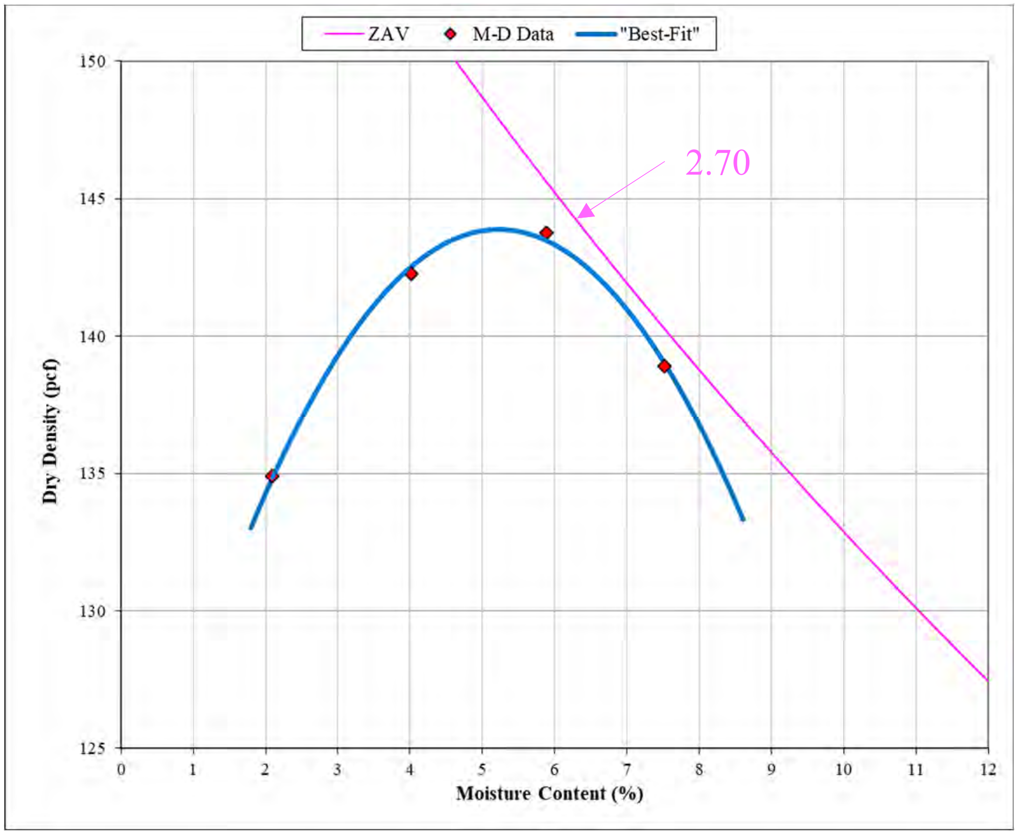


D10	0.089
D30	2.053
D60	11.700

Cu	131.4
Cc	4.0

Raw Base Course Materials

- Proctor (Tex-113-E)

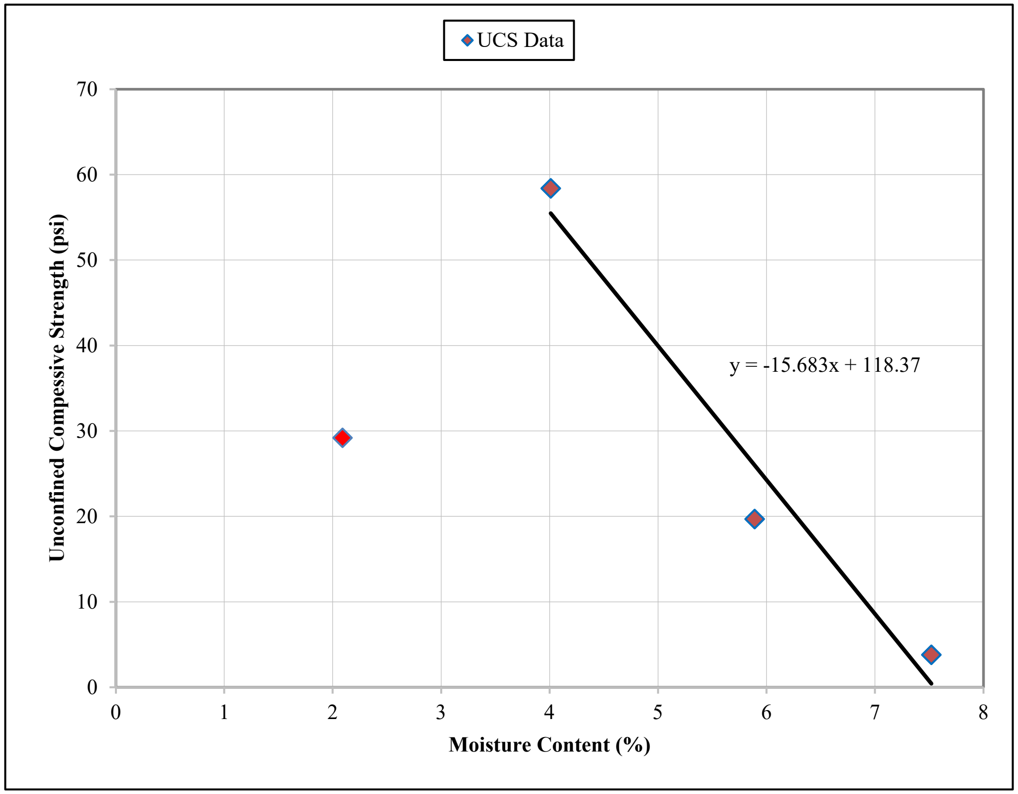


Water Content (%)	2.1	4.0	5.9	7.5
Dry Density (pcf)	134.9	142.3	143.8	138.9

Maximum Dry Density (pcf)	143.9
Optimum Water Content (%)	5.2
M-D Graph R^2	1.00

Raw Base Course Materials

- Unconfined Compression

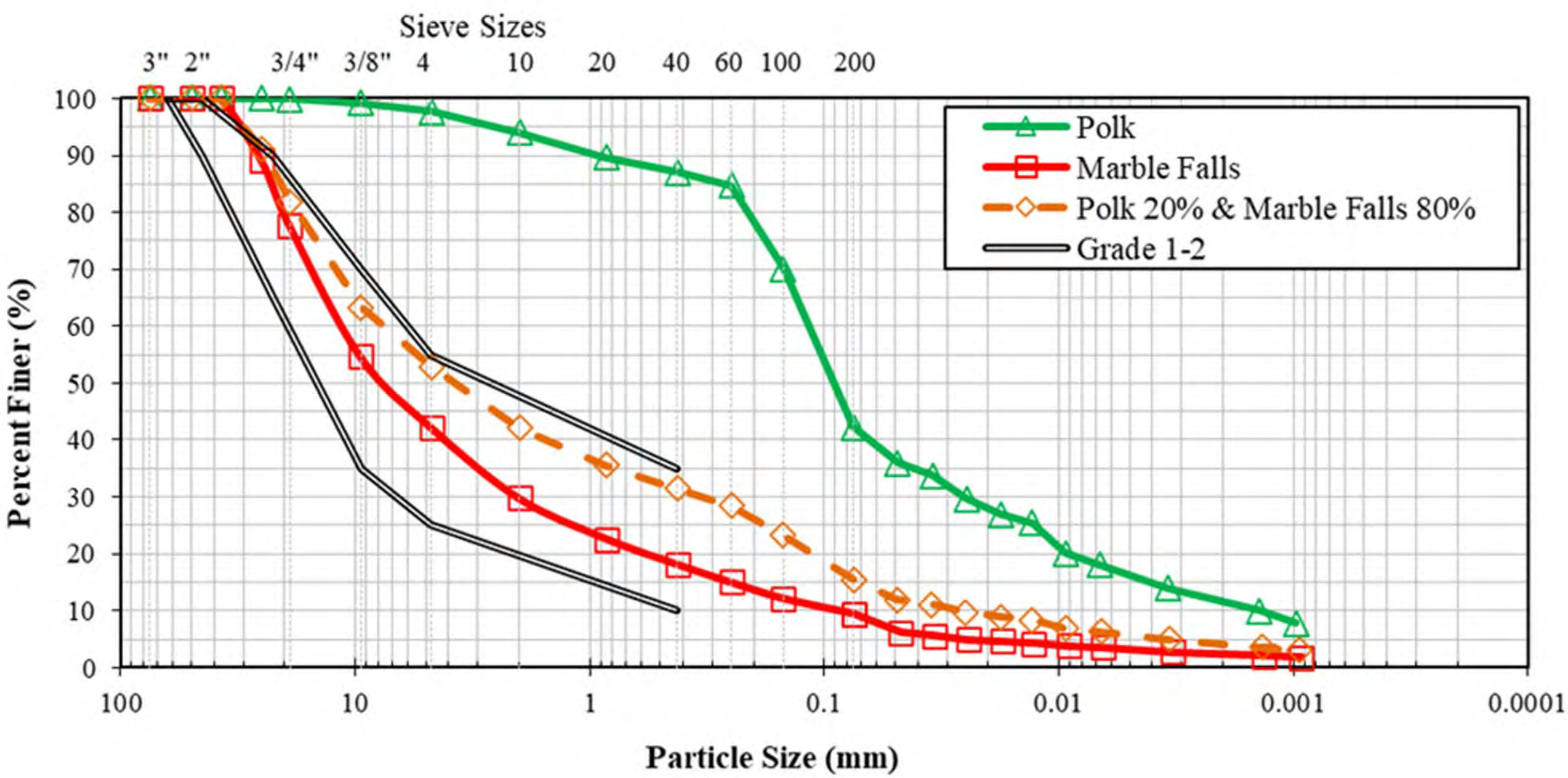


2.1% WC before test (too dry)

Water Content (%)	2.1	4.0	5.9	7.5
Unconfined Strength (psi)	29.8	59.6	20.3	3.9
Strain (%)	2.1	2.1	3.1	3.1

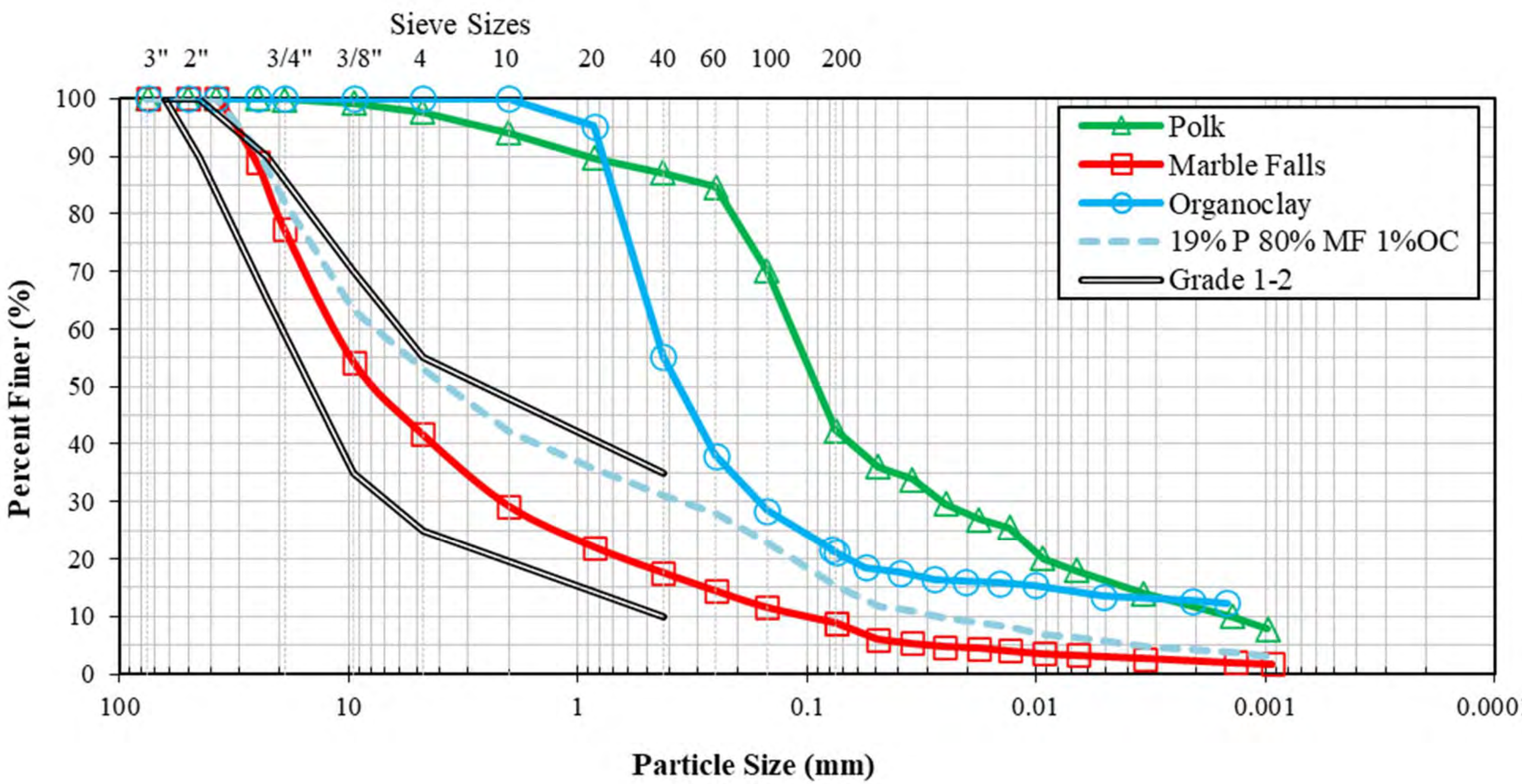
Blended Base Course Materials

- Blended gradation curve:



Blended Base Course Materials

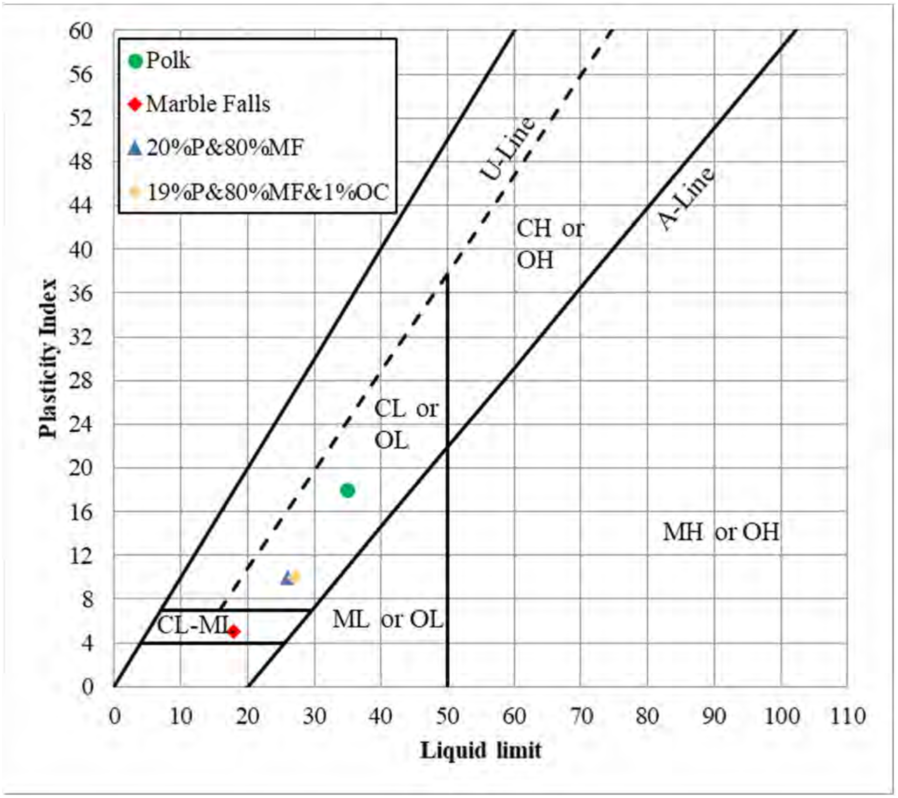
- Blended gradation curve (with Organoclay):



Blended Base Course Materials

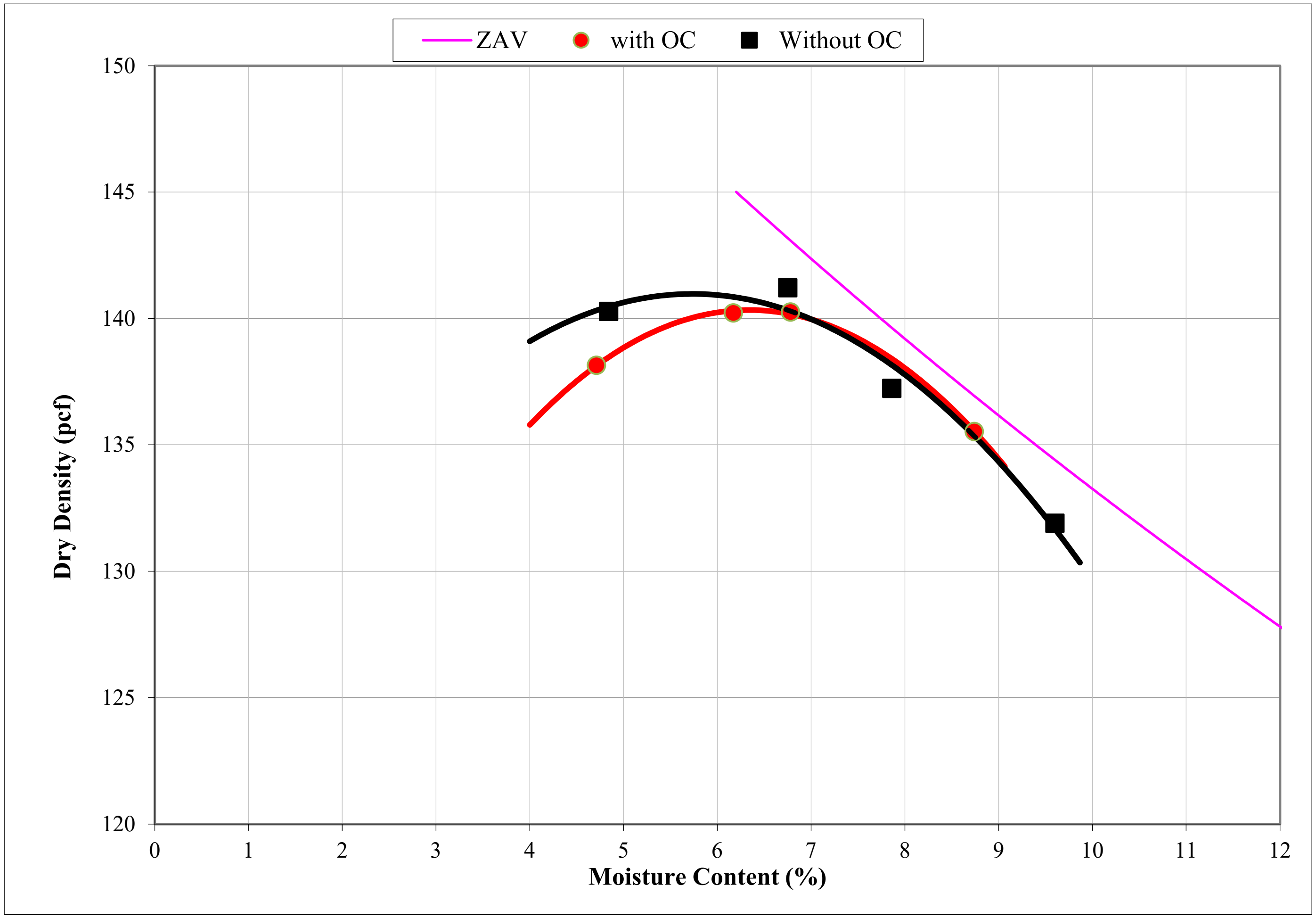
- Atterberg limits:

Trial	Polk	Marble Falls	20% P 80% MF	19% P 80% MF 1% OC
LL(%)	35	18	26	27
PL(%)	17	13	16	17
PI(%)	18	5	10	10
LS(%)	7	4	5	6
Type	CL	CL-ML	CL	CL
USCS	SC	GW-GM	GC	GC



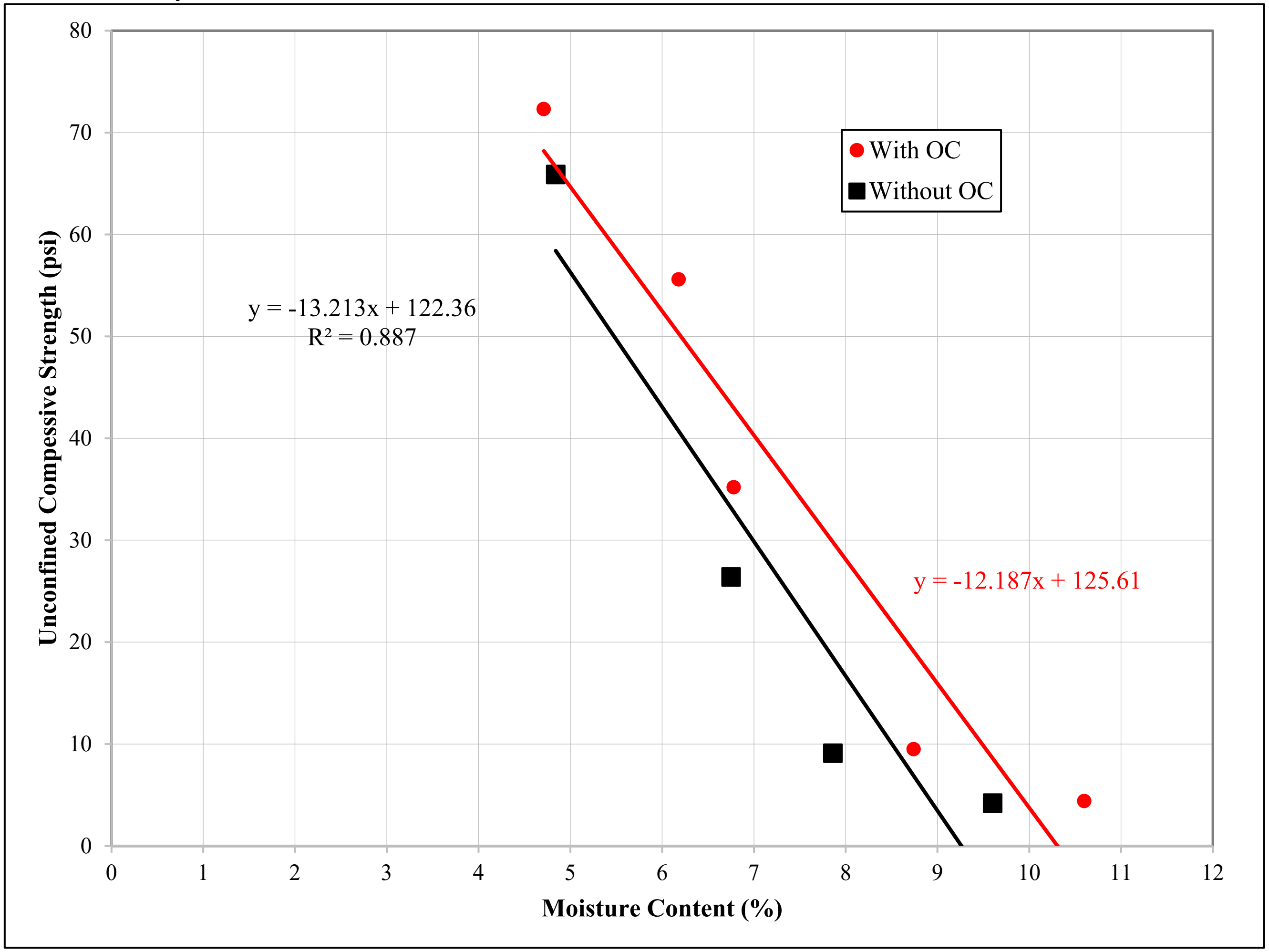
Blended Base Course Materials

- Proctor (Tex-113-E)



Blended Base Course Materials

- Unconfined Compression for Tex-113-E



Blended Base Course Materials

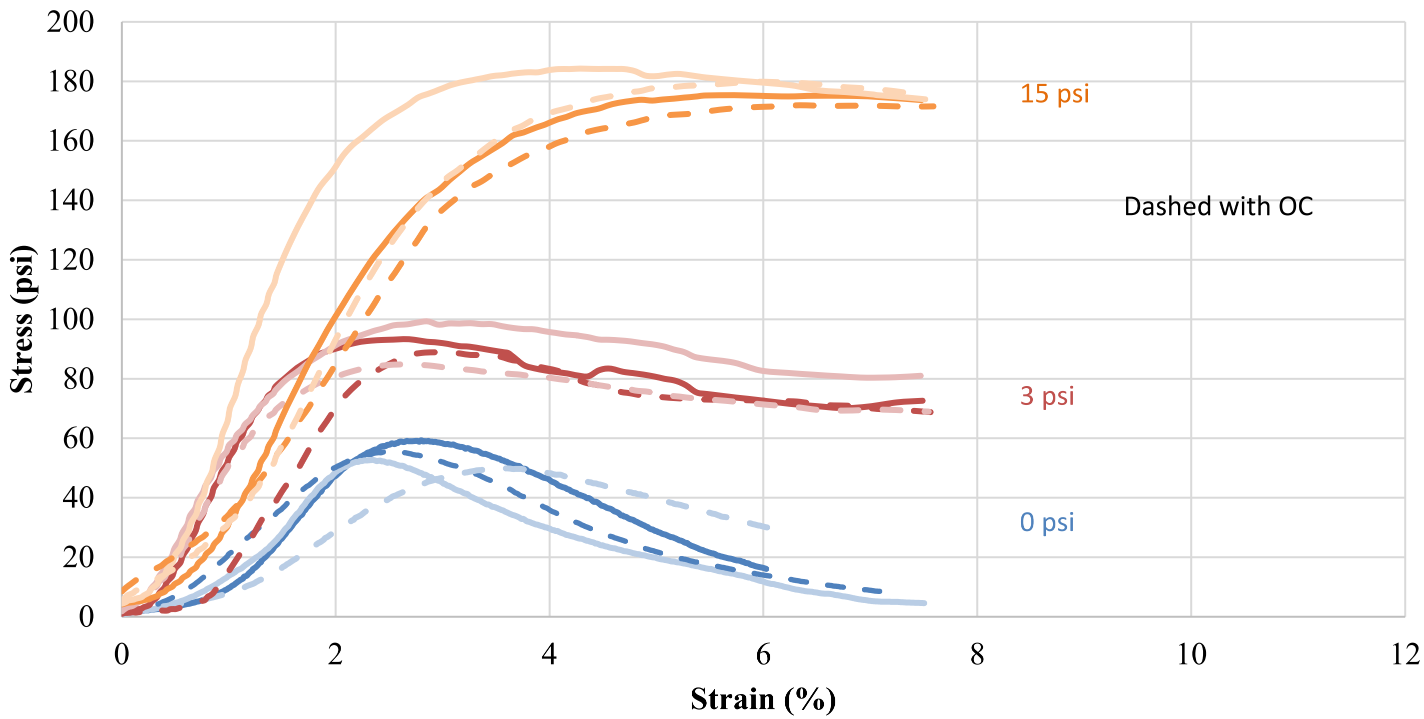
- Wet ball mill test:

Water Content (%)	Wet ball Mill		Wash Sieve Analysis	
	1	2	1	2
Wihtout OC Strain (%)	40	40	33	33
With OC Strain (%)	42	42	34	34

  – The average wet ball mill value increase from 33% in the proportion passing the No. 40 sieve.

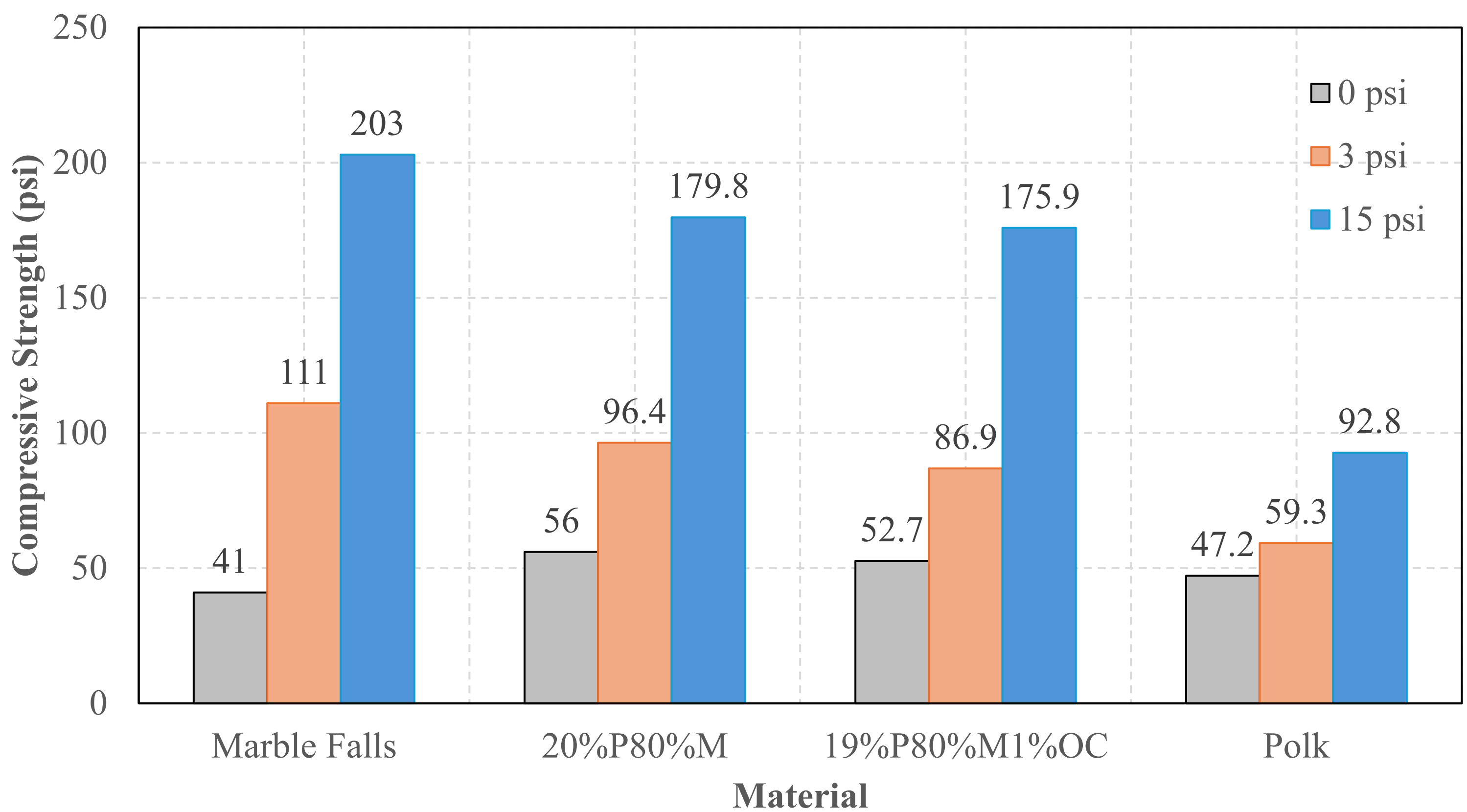
Blended Base Course Materials

- Texas triaxial test:



Blended Base Course Materials

- Texas triaxial test:



Base Materials

- TxDOT Item 247: Flexible Base

Property	Test Method	Grade 1–2	Grade 3	Grade 4[2]	Grade 5
Sampling	Tex-400-A				
Master gradation sieve size (cumulative % retained)	Tex-110-E				
2-1/2"		0	0	As shown on the plans	0
1-3/4"		0–10	0–10		0–5
7/8"		10–35	–		10–35
3/8"		30–65	–		35–65
#4		45–75	45–75		45–75
#40		65–90	50–85		70–90
Liquid Limit, % Max	Tex-104-E	40	40	As shown on the plans	35
Plasticity Index, Max[1]	Tex-106-E	10	12	As shown on the plans	10
Plasticity index, Min[1]		As shown on the plans	As shown on the plans	As shown on the plans	As shown on the plans
Wet ball mill, % Max	Tex-116-E	40	–	As shown on the plans	40
Wet ball mill, % Max increase passing the #40 sieve		20	–	As shown on the plans	20
Min compressive strength, psi	Tex-117-E			As shown on the plans	
lateral pressure 0 psi		35	–		–
lateral pressure 3 psi		–	–		90
lateral pressure 15 psi		175	–		175

1. Determine plastic index in accordance with Tex-107-E (linear shrinkage) when liquid limit is unattainable as defined in Tex-104-E.
2. Grade 4 may be further designated as Grade 4A, Grade 4B, etc.

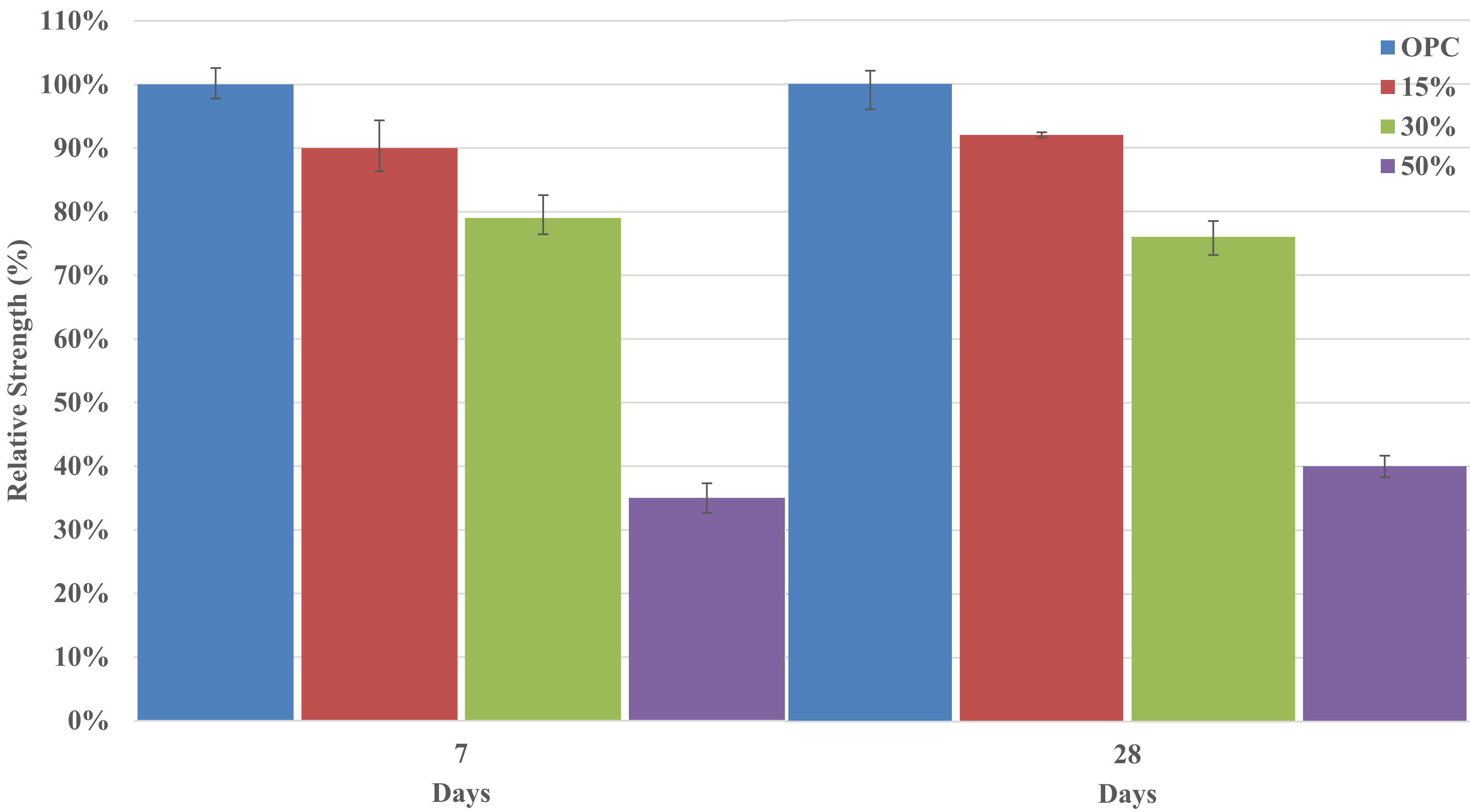
Material Performance after Treatment

USE IN CONCRETE AS FINE AGGREGATE

Concrete Testing

- Four concrete mixtures were prepared for compressive strength testing.
- OPC mixture was the control (w/c=0.6, sand-to-cement ratio 2.75, 28 days compressive strength of 3000 psi)
- The fine aggregates constitute 30% of the total weight of the concrete mix (excluding water).
- Mixtures with 15, 30, and 50% replacement levels of fine aggregates were prepared.

Concrete Testing



Concrete Testing

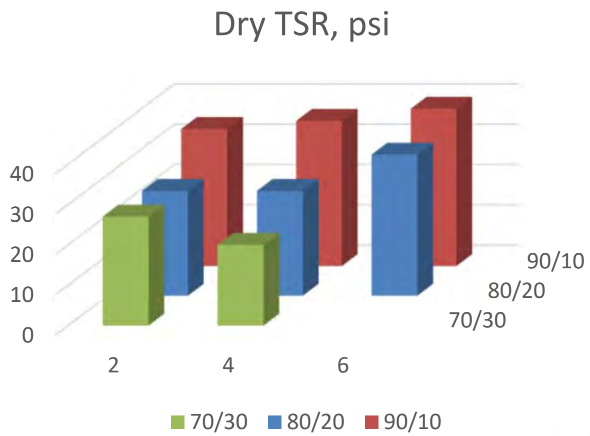
- Four concrete mixtures were prepared for compressive strength testing.
- OPC mixture was the control (w/c=0.6, sand-to-cement ratio 2.75, 28 days compressive strength of 3000 psi)
- The fine aggregates constitute 30% of the total weight of the concrete mix (excluding water).
- Mixtures with 15, 30, and 50% replacement levels of fine aggregates were prepared.
- Up to 30% replacement of fine aggregates with drill cuttings met the desired target strength of 3000 psi. However, the 50% replacement mixture required more water (w/c=0.75) and failed to met the target strength.

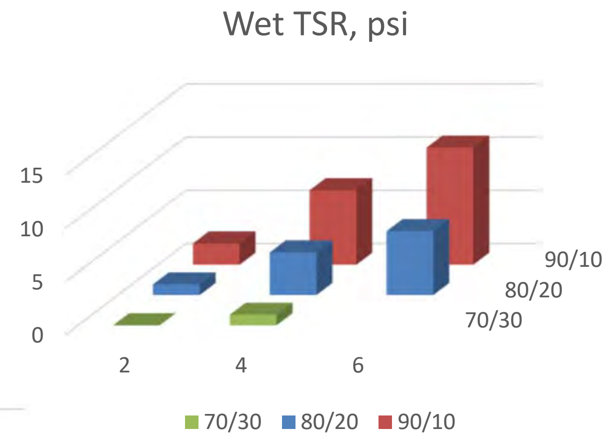
Material Performance after Treatment

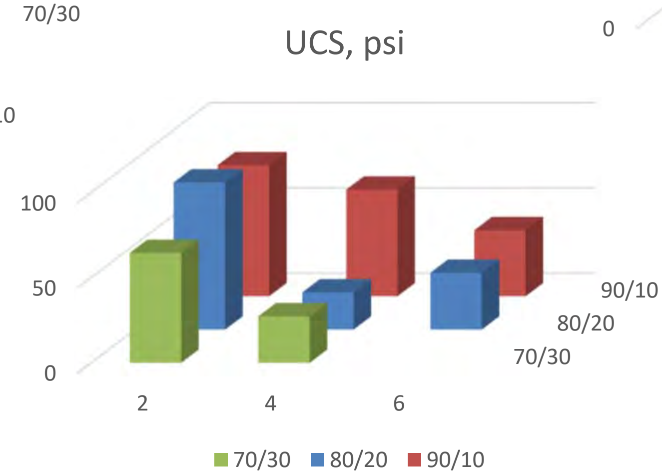
STABILIZATION FOR ASPHALT / ASPHALT CONCRETE

Stabilization with Admixtures-Asphalt

Mixture Property[1]	Test Method	Minimum Requirement
Indirect Tensile Strength (IDT) psi	Provided by MTD	50
Moisture Conditioned[2] IDT, psi		30
Moisture Conditioned[2] Unconfined Compressive Strength (UCS)[3], psi		120







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Material Performance after Treatment

ENVIRONMENTAL TESTING

Environmental Characterization

- Leaching Testing
  - Leaching Environmental Assessment Framework (LEAF)
    - Toxicity Characteristic Leachate Procedure (TCLP) is the required test method for hazardous waste, but LEAF tests provide more flexibility by evaluating leaching under a wider range of environmental conditions
    - EPA encourages the use of LEAF to evaluate the potential for adverse impacts to human health or the environment
  - EPA SW-846 Test Method 1313 - Liquid-Solid Partitioning as a Function of Extract pH Using a Parallel Batch Extraction Procedure
    - Liquid-to-solid ratio of 10
    - Granular material
    - Extracts of solid material (i.e., the eluates) tested for Total Organic Carbon (non-purgeable organic carbon, NPOC)
  - EPA SW-846 Test Method 1315: Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials Using a Semi-Dynamic Tank Leaching Procedure
    - Liquid-to-surface area ratio (L/A) of 9 ± 1 mL / cm^2
    - Monolithic material (cylindrical mortar specimens)
    - These tests were performed on the Concrete Specimens

Total Organic Carbon

- LEAF 1313 Eluate
- P-1, -2: Polk drill cuttings
- LRA: limestone rock asphalt
- RAP: reclaimed asphalt pavement
- L: lime (1.2 g)
- L3%7d, 28d: lime stabilized drill cuttings, 3% wt. lime, 7-d and 28-d
- OC: Organoclay
- OC 1%-5%: Organoclay stabilized drill cuttings, % wt.

Material	NPOC (ppm)	pH
P-1	19.61 ± 0.090	7.82 ± 0.03
P-2	17.53 ± 0.222	7.83 ± 0.03
LRA	4.48 ± 0.194	8.19 ± 0.11
RAP	5.70 ± 0.751	8.14 ± 0.26
L	0.19 ± 0.007	12.73 ± 0.02
L3%7d-1	11.62 ± 0.012	12.54 ± 0.01
L3%7d-2	11.72 ± 0.053	12.56 ± 0.00
L3%28d	12.84 ± 0.110	12.10 ± 0.03
OC	3.69 ± 0.179	8.43 ± 0.13
OC1%	13.97 ± 0.205	7.52 ± 0.06
OC2%	12.06 ± 0.380	7.86 ± 0.01
OC3%	10.77 ± 0.055	7.70 ± 0.20
OC5%	10.29 ± 0.803	7.65 ± 0.00

Total Organic Carbon

- OC 1%-5%12d: Organoclay stabilized drill cuttings, cured for 12 days, % wt.
- New OC 1%-5%: Organocaly from a different source, % wt.
- Cement 4%-10%: Cement stabilized drill cuttings, % wt.

Material	NPOC (ppm)
OC1%12d	16.61
OC2%12d	19.04
OC3%12d	19.86
OC5%12d	21.95
newOC1%	21.11
newOC2%	18.71
newOC3%	17.24
newOC5%	14.82
cement 4%	45.99
cement6%	44.39
cement8%	41.06
cement10%	39.04

Trace Metal Concentrations

- LEAF 1313 Eluate
- ICP-MS
  (Standard Method 3125)
- Trace metal grade nitric acid was used for dilution and sample preparation

- DC1, DC2: drill cuttings
- LRA1, 2: limestone rock asphalt
- RAP: reclaimed asphalt pavement
- Lime1, 2 & 3: lime 3%, 7 day cured
- L28-1 & 2: lime 3%, 28 day cured

ICP-MS Results in ppb

Sample	Li	Mg	Al	K	Ca	Cr	Fe	Co	Ni	Cu	Zn	As	Se	Sr	Cd	Ba	Pb
DMS			24000			100		1500	490	1300	7300	10	50		5	2000	15
DC1	17.7	8820		8530	12500			3.35	17.3	8.40			4.77	7520		43.4	
DC2	21.5	8550	10.1	8340	12200			4.39	9.46	6.62			21.0	7350		45.4	
LRA1	1.80	3750	68.6	2380	2470								1.49	427		27.7	
LRA2	3.57	6430	32.1	5950	3870			3.86	1.48					653		39.4	
RAP	1.19	1160	378	1270	1030	6.30	181			5.90			1.88	73.1		12.3	12.4
Lime1	14.3	84.2	94.7	67200	56400			52.1	124	94.4			38.8	50000		1550	50.3
Lime2			108	6310	53000				49.5	93.4				48600		1500	
Lime3			87.8	31900	58300				307	566				173000		6000	
L28-1			762	8910	43200			9.68	70.6	131				44100		904	
L28-2	11.9	313	1090	10300	53200			14.3	88.9	173			37.7	49700		1220	39.4

DMS 11000, leachate concentrations for traditional construction materials (ug/L). Values in the table are for Asphaltic Binders (same or lower than aggregates and cementitious materials)

Trace Metal Concentrations

- LEAF 1313 Eluate
- ICP-MS (Standard Method 3125)
- Trace metal grade nitric acid was used for dilution and sample preparation

- OC: organoclay / OC1-5%: organoclay % wt.
- o-OC1-5%: organoclay % wt., cured for 12 days
- n-OC1-5%: organoclay from a different source, % wt.

ICP-MS Results in ppb

Sample	Li	Mg	Al	K	Ca	Cr	Fe	Co	Ni	Cu	Zn	As	Se	Sr	Cd	Ba	Pb
DMS			24000			100		1500	490	1300	7300	10	50		5	2000	15
DC1	17.7	8820		8530	12500			3.35	17.3	8.40			4.77	7520		43.4	
DC2	21.5	8550	10.1	8340	12200			4.39	9.46	6.62			21.0	7350		45.4	
LRA1	1.80	3750	68.6	2380	2470								1.49	427		27.7	
LRA2	3.57	6430	32.1	5950	3870			3.86	1.48					653		39.4	
RAP	1.19	1160	378	1270	1030	6.30	181			5.90			1.88	73.1		12.3	12.4
OC	20.9	11700		2150	7890									2760			
OC1%	15.4	7660		8390	13200				7.85	5.79			2.1	8790		55.1	
OC2%	20.8	7890		8760	13200				8.21	5.97	6.63		2.4	8810		50.5	
OC3%	14.9	7890		8000	13100				8.14	5.10			2.50	8440		47.5	
OC5%	16.8	8340		8010	13300				8.40	5.13	6.31		2.94	8760		48.5	
o-OC1%	22.0	8500		7940	14000			0.965	9.58	10.4	5.04		2.25	8550		257	
o-OC2%	18.2	8570		8710	14000				8.33	8.54			2.06	9080		52.8	
o-OC3%	17.9	9420		8370	15000				8.75	8.37			2.34	8890		49.9	
o-OC5%	19.5	9950	23.5	8540	15500				8.11	7.40			2.50	9340		51.7	
n-OC1%	18.5	9360		10200	15100				8.94	6.75			2.89	8610		47.9	123
n-OC2%	17.8	8770		9710	14200				8.67	6.15			2.17	8480		48	
n-OC3%	18.3	9850		10600	16500				9.40	6.41			2.1	9400		50.9	
n-OC5%	21.4	9750		10200	16300				8.95	6.27			2.14	9060		46.1	

Semivolatile Organic Compounds

Detection Summary, LEAF 1313 Eluate

Material	Analyte	Result	Qualifier	RL	MDL	Unit	Dil Fac	Method
Drill Cuttings	2, 4, 6-Trichlorophenol	0.00409	J	0.0100	0.00189	ppm	1	8270E
	Benzoic acid	0.0535	J	0.0600	0.00430			
	Di-n-butyl phthalate	0.00235	J	0.0100	0.00226			
Drill Cuttings (LEAF 1314 Eluate)	2, 4, 6-Trichlorophenol	0.00200	J	0.00500	0.000946	ppm	1	8270E
RAP	Benzoic acid	0.0515	J	0.0600	0.00430	ppm	1	8270E
LRA	No detections							
Lime	Benzoic acid	0.0450	J	0.0300	0.0189	ppm	1	8270E
Lime 3%	2, 4, 6-Trichlorophenol	0.00566	J	0.0100	0.00189	ppm	1	8270E
	2, 4-Drichlorophenol	0.00218	J	0.0100	0.00208			
	Benzoic acid	0.0660	*-	0.0600	0.00430			
	Naphthalene	0.00162	J	0.0100	0.00150			
Cement Paste	Benzoic acid	0.0236	J	0.0300	0.0189	ppm	1	8270E
Cement 4%	2, 4, 6-Trichlorophenol	0.00209	J	0.0100	0.00189	ppm	1	8270E
	Benzoic acid	0.0968	*-	0.0600	0.00430			
Cement 10%	Benzoic acid	0.0985	*-	0.0600	0.00430	ppm	1	8270E

RL: Reporting Limit, MDL: Method Detection Limit, Dil Fac: Dilution Factor
J: result is less than the RL but greater than or equal to the MDL and the concentration is an approximate value
*-: Laboratory Control Samples and/or Sample Duplicates are outside acceptance limits, low biased

Total Petroleum Hydrocarbons

TCEQ Method 1005, LEAF 1313 Eluate

Material	Analyte	Result	Qualifier	RL	MDL	Unit	Dil Fac	Method
Drill Cuttings 1	>C12-C28 Range Hydrocarbons	1.74	J	5.45	0.941	ppm	1	TX 1005
	Total Petroleum Hydrocarbons (C6-C35)	1.74	J	5.45	0.965			
Drill Cuttings 2	>C12-C28 Range Hydrocarbons	1.72	J	5.34	0.921	ppm	1	TX 1005
	Total Petroleum Hydrocarbons (C6-C35)	1.72	J	5.34	0.945			
RAP	No detection							
LRA	>C12-C28 Range Hydrocarbons	1.32	J	4.66	0.804	ppm	1	TX 1005
	Total Petroleum Hydrocarbons (C6-C35)	1.32	J	4.66	0.825			
Cement 4%	>C12-C28 Range Hydrocarbons	2.88	J	5.58	0.962	ppm	1	TX 1005
	Total Petroleum Hydrocarbons (C6-C35)	2.88	J	5.58	0.987			
Cement 10%	>C12-C28 Range Hydrocarbons	2.21	J	5.28	0.912	ppm	1	TX 1005
	Total Petroleum Hydrocarbons (C6-C35)	2.21	J	5.28	0.935			

RL: Reporting Limit, MDL: Method Detection Limit, Dil Fac: Dilution Factor

J: result is less than the RL but greater than or equal to the MDL and the concentration is an approximate value

*-: Laboratory Control Samples and/or Sample Duplicates are outside acceptance limits, low biased

Volatile Organic Compounds

Detection Summary, LEAF 1315 Eluate

Material	Analyte	Result	Qualifier	RL	MDL	Unit	Dil Fac	Method
Control, interval 1	No detections							
Control, interval 2	No detections							
15%, interval 1	No detections							
15%, interval 2	No detections							
30%, interval 1	No detections							
30%, interval 2	No detections							

RL: Reporting Limit, MDL: Method Detection Limit, Dil Fac: Dilution Factor
J: result is less than the RL but greater than or equal to the MDL and the concentration is an approximate value
*-: Laboratory Control Samples and/or Sample Duplicates are outside acceptance limits, low biased

- EPA Method 8260C
- Gas Chromatography / Mass Spectrometry (GC-MS)

Semivolatile Organic Compounds

Detection Summary, LEAF 1315 Eluate

Material	Analyte	Result	Qualifier	RL	MDL	Unit	Dil Fac	Method
Control, interval 1	No detections							
Control, interval 2	No detections							
15%, interval 1	Di-n-butyl phthalate	0.942	J	1.14	0.765	ppb	1	8270E
15%, interval 2	No detections							
30%, interval 1	No detections							
30%, interval 2	No detections							

RL: Reporting Limit, MDL: Method Detection Limit, Dil Fac: Dilution Factor
J: result is less than the RL but greater than or equal to the MDL and the concentration is an approximate value
*-: Laboratory Control Samples and/or Sample Duplicates are outside acceptance limits, low biased

- EPA Method 8270E
- Gas Chromatography / Mass Spectrometry (GC-MS)

Total Petroleum Hydrocarbons

Detection Summary, LEAF 1315 Eluate

Material	Analyte	Result	Qualifier	RL	MDL	Unit	Dil Fac	Method
Control, interval 1	No detections							
Control, interval 2	No detections							
15%, interval 1	No detections							
15%, interval 2	No detections							
30%, interval 1	No detections							
30%, interval 2	No detections							

RL: Reporting Limit, MDL: Method Detection Limit, Dil Fac: Dilution Factor
J: result is less than the RL but greater than or equal to the MDL and the concentration is an approximate value
*-: Laboratory Control Samples and/or Sample Duplicates are outside acceptance limits, low biased

- TCEQ Method 1005
- Gas Chromatography

Exhibit 46.04

This exhibit was not previously submitted in November 2023

American Zinc

Site Summary

The American Zinc site is located near the city of Dumas, approximately 3.5 miles north on U.S. 287 and 5 miles east on Farm Road 119. The site operated as a zinc smelter from the late 1930s until the late 1960s or early 1970s, generating heavy metal waste typical to that process. Numerous slag piles were deposited in, around, and across the intermittent South Palo Duro Creek. The slag material was also used throughout the site as road base. In 1987, the TCEQ collected samples from various locations around the site, including the creek, and analysis showed significant contamination.

Superfund Registry and Investigation

In October 1993, the TCEQ proposed the site to the state Superfund registry. The potentially responsible parties entered into an Agreed Order in 1995 and Agreed Order Amendment in 1999 with the TCEQ to conduct the remedial investigation and feasibility study. The remedial investigation and feasibility study began in July 1995.

Remedial Action

In January 2010, the site was listed on the state Superfund registry and the TCEQ issued an administrative order, which selected the remedial action for the site and ordered named responsible parties to perform it. The selected remedial action specified a commercial/industrial land use and entailed consolidation of soils, capping of contaminated areas, land use restrictions, and soil treatments. The remediation work began in May 2012 and was completed in June 2012.

Current Status

Cleanup is complete and the site is in the operation and maintenance phase. Responsible parties continue to maintain the site and monitor the capped area and surrounding area to prevent further contamination.

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Exhibit 46.05

This exhibit was not previously submitted in November 2023

The following is an Adobe Acrobat reproduction of the official

Community Relations Plan

for

American Zinc

No graphic illustrations are included with this electronic version, but are available with the printed versions as part of the American Zinc repository records

at

Killgore Memorial Library
124 S. Bliss Avenue
Dumas, Texas
and/or
TNRCC Records Management Center
Austin, Texas

September 2000

Scroll Down to View

COMMUNITY RELATIONS PLAN
for
American Zinc Proposed State Superfund Site
North of Dumas, Moore County, Texas

Updated June 1999

Overview of Community Relations Plan

This community relations plan (CRP) identifies issues of community concern regarding the American Zinc Proposed State Superfund site (American Zinc), north of the town of Dumas in Moore County, Texas. It also outlines the anticipated community relations activities to be conducted during each phase of the cleanup at the American Zinc site.

The American Zinc community relations plan has been prepared to aid the Texas Natural Resource Conservation Commission (TNRCC) in developing a community relations program tailored to the needs of the community affected by the American Zinc site. The TNRCC will conduct community relations activities to ensure that the local public has input to decisions and access to information about Superfund activities at the American Zinc site.

The information in this plan is based primarily on the Hazard Ranking System (HRS) package. This plan will be updated periodically during the course of the cleanup.

Site Profile

Latitude/Longitude: 35B 56' 39'' N, 101B 55' 59'' W

Site Location and Description:

The American Zinc Proposed State Superfund site is located approximately 3.5 miles north on U.S. Highway 287 and 5 miles east on F.M. 119 from the town of Dumas in Moore County in the Texas panhandle.

The American Zinc Proposed State Superfund site is an abandoned zinc smeltering plant that occupies in excess of 160 acres. The facility was in operation from the late 1930's until the late 1960's or early 1970's, generating heavy metal waste typical to the smelting process. Numerous slag piles have been deposited in, around, and across the intermittent South Palo Creek.

Background and Operating History:

The American Zinc Company started operations as a zinc smelting plant in the late 1930's. The site was originally developed by Illinois Zinc Company and then sold to Peru Mining Company in September 1939. In March 1943, the Peru Mining Company of Illinois conveyed the site to the American Zinc Company. This conveyance was subject to a lease agreement dated July 31, 1942, between the Peru Mining Company and the Defense Plant Corporation, a corporation created by the Reconstruction Finance Corporation Act, as Amended, to aid the U.S. Government in its national defense program. The smelting plant was used for the major part of its lifetime serving the "war effort" during World War II. Italian prisoners of war were used as the labor force during the war.

In 1957 the smelting plant was declared surplus and assigned to the Administrator of General Services for disposal pursuant to the Federal Property and Administrative Service Act of 1949. The U.S. Government and Reconstruction Finance Corporation conveyed its leasehold interest for the site to the American Zinc, Lead and Smelting Company in a bill of sale dated November 5, 1958.

After the site was decommissioned American Zinc Company sold the site to W.R. Pendleton and Clark A. Pendleton through public auction on December 14, 1971.

On May 2, 1985, Extraction Systems of America purchased part of the site. All improvements, scrap material and residue located on that portion of the property were included in the Deed of Trust. On December 8, 1988, Extraction Systems of America and Extraction Systems, Ltd., conveyed property of the May 1985 sale back to W.R. Pendleton and wife, Mozelle Pendleton in lieu of foreclosure.

On at least one occasion, slag material from the American Zinc has been sold and used as road base material. Sometime between 1973 and 1974 the Texas Department of Highway and Public Transportation (TDHPT), predecessor agency to the Texas Department of Transportation (TxDOT), used purchased zinc smelter residue material from the site as road base within the Dumas city limits.

Over the years since the plant's closing, an unknown number of private individuals have also taken slag and other waste-type materials from the site to use as bed-lining for home driveways, flower beds and lawns.

The TWC became aware of the American Zinc site in the fall of 1987 when a Texas Water Commission (TWC), TNRCC predecesor agency, field inspector drove by the site while traveling to an unrelated inspection.

On November 19, 1987 the TWC performed a sampling event at the site. During this sampling event the TWC collected a creek sediment sample, soil sample and solid waste composite sample from various locations around the site. The analysis results indicated significant contamination from lead and cadmium on site.

In August 1989, the TWC and TDHPT made four soil borings along the roadways, within the city of Dumas, that received slag material as roadbase. The results from those borings indicated contamination from lead and cadmium.

On September 6, 1989, TWC personnel collected four additional creek sediment samples from the South Palo Duro Creek. One sample was collected upstream of the waste piles for a representation of background. The three remaining samples were collected downstream on the adjacent properties to the north of the American Zinc site. The results of this sampling event revealed a sediment sample containing cadmium significantly exceeding background within one mile of the site. Sediment samples collected one mile downstream of the waste piles revealed greatly enhanced levels of cadmium and lead over sediment samples collected upstream of the waste piles. Sediment samples as far as three miles downstream showed high levels of cadmium and lead.

The Hazard Ranking System Assessment for the American Zinc site was completed in March 1993. On November 16, 1993 the Texas Natural Resource Conservation Commission (TNRCC), successor agency to the TWC, held a public meeting in Dumas to announce TNRCC intentions to propose the American Zinc site to the State Superfund Registry.

The Texas Natural Resource Conservation Commission (TNRCC) was notified by the residents of Dumas of the presence of slag/retort material in yards during a public meeting for the notification of registry listing for the American Zinc site. Six residential yards and one commercial property were originally identified for sampling by the TNRCC. Of these six yards, four were found to have levels of contaminants that the Texas Department of Health (TDH) indicated would be "prudent" to remove from the yards. The commercial property was addressed by the property owner. The TDH was requested to perform a health consultation, which resulted in the TDH recommendation that the slag/retort material in the four yards be removed.

The four residences recommended for remediation were located in Dumas on Bennett Street, 5th Street and Carson Street. A farm located in far north Moore County was also listed for slag/retort removal. The removals took place in October and November 1997.

The remedial action to be performed at each residence included:

- Documentation/Inventory of Existing Site Conditions
- Excavation and Staging of Soil/Retort Material
- Backfilling of Excavated Areas with Clean Imported Fill Material
- Restoration of Site to Previous Grade and Condition
- Sampling and Analysis of the Staged Soil/Retort Material
- Waste Characterization of Staged Soil/Retort Material
- Transportation and Disposal of Contaminated Soil/Retort Material

A state approved contractor was enlisted by the state to perform the slag/retort removal from the yards and farm.

Summary of the removal action at the farm located in far north Moore County

The contractor began the project by performing excavation activities at the farm. The area of concern at the farm was comprised of one large affected area consisting of 8,400 square feet. The proposed area of excavation was located between the farm equipment storage warehouse and residence. Excavation in this area was performed using a trackhoe. The excavated soil/retort material was removed in 6 inches lifts and inspected by the on-site TNRCC representative to estimate the depth of the contamination. A total of 375 cubic yards of slag/retort material was excavated and stockpiled on polyethylene sheeting for sampling and analysis. The affected area was excavated to a depth of 12 inches. The base of the excavation was inspected by the TNRCC representative and visually observed to be free of contaminants. Samples were collected from the base of the excavation and submitted for analytical analysis and the results indicated 18 parts per million (ppm) and 16 ppm Arsenic, 7 ppm and <5 ppm Cadmium, 9 ppm and 15 ppm Lead and 1,200 ppm and 3,000 ppm Zinc. Samples were also collected from the stockpiled sod and submitted for analytical analysis for waste characterization. After samples were collected from the stockpiled soil/retort material, the stockpiled soil/retort material was encapsulated in polyethylene sheeting and weighted to ensure that the plastic remained on the stockpile during staging.

Upon completion of the excavation activities and confirmation of cleanliness by the analytical results, the area was backfilled with sand and covered with 1.5 inch unwashed gravel. A total of 200 cubic yards of fill sand and 167 cubic yards of unwashed gravel were placed and compacted in the excavation. A sample was collected from the backfilled material and submitted to the laboratory for analytical analysis. The backfilled area was inspected and approved by the TNRCC and the property owner and no further remedial action was required at this location.

Summary of the removal action at the residence located in Dumas on 5th Street

Remedial action at this residence consisted of one affected area. The affected area consisted of a small stretch of property adjacent to the rear driveway and backyard fence comprised of a total of 1,175 square feet. Prior to excavation, the contractor prepared an inventory list of all personal belongings located in the affected area. All personnel belongings in the affected area requiring removal for excavation were removed from the affected area and replaced upon the completion of excavation and backfilling. Excavation activities were performed at this location using a backhoe. The excavated soil/retort material was removed in 6 inch lifts and inspected by the on site TNRCC representative to determine the depth of contamination. A total of 20 cubic yards of slag/retort material was removed from the contaminated area. The affected material was removed to a depth of 6 inches and inspected by the TNRCC representative. Upon inspection by the TNRCC representative, it was determined that the soil was visually free of contaminants. The excavated slag/retort material was placed in roll-off boxes and staged for sampling and waste characterization at the City of Dumas Landfill, as per agreement with the City of Dumas. Upon completion of the excavation activities, samples were collected from the base of the excavation and submitted for analytical analysis and the results indicated 16 ppm and 22 ppm Arsenic, <5 and 5 ppm Cadmium, <5 and <5 ppm Lead and 120 and 1,900 ppm Zinc.

Upon completion of excavation activities and confirmation of cleanliness from the analytical results, the excavated area was backfilled with 20 cubic yards of 1.5 inch unwashed gravel. The entire backfilled area was compacted and leveled using a backhoe. Upon completion of the backfilling activities, the entire area was inspected by the on site TNRCC representative and property owner. It was agreed that no further remedial action was required at this location.

Summary of the removal action at the residence located in Dumas
on Carson Street

This residence consisted of three affected areas. The affected areas consisted of the entire front and portions of both side yards comprising a total of 1,715 square feet. Prior to excavation, the contractor prepared an inventory list of all personal belongings located in the affected area. All personal belongings in the affected area requiring removal for excavation were removed from the affected area and replaced upon the completion of excavation and backfilling. Excavation activities at this location were performed using a backhoe, mini--excavator and hand labor. The excavation included the complete removal of the lava rock cover located over the proposed excavated area. The lava rock located over the excavated area was a combination of small and large pieces of slag/retort material and required disposal of the entire material to ensure all slag/retort material had been removed. The excavated slag/retort material was removed in 6 inch lifts and inspected by the on site TNRCC representative to determine the depth of contamination. A total of 30 cubic yards of slag/retort material was removed from the residence. The affected material was removed to a depth of 6 inches. Upon completion of the excavation, the excavated area was inspected by the TNRCC representative for the presence of contaminants. Upon the inspection, the base of the excavation was determined to be visually free of contaminants. The excavated slag/retort material was placed in roll-off boxes and staged for sampling and waste characterization at the City of Dumas Landfill, as per agreement with the City of Dumas. Samples were collected from the base of the excavation and submitted to the laboratory for analytical analysis and the results indicated 12 ppm and 15 ppm Arsenic, <5 ppm and <5 ppm Cadmium, <5 ppm and <5 ppm Lead and 330 ppm and 34 ppm Zinc.

Upon completion of the excavation and confirmation of cleanliness by the analytical results, the excavated area was backfilled with 22 cubic yards of sand to 3 inches below grade. The contractor placed polyethylene sheeting over the backfilled sand and covered the remaining area with 16 cubic yards of black lava rock. The lava rock was placed in a manner to ensure the area was returned to its original state prior to excavation. Two affected areas were backfilled with sand and lava rock. The north affected area near the driveway was backfilled with 4 cubic yards of top soil. Upon completion of the backfilling, the area was inspected by the on site TNRCC representative and property owner. It was agreed that no further remedial action was required at this location.

Summary of the removal action at the residence located in Dumas
on Bennett Street

The remedial action performed at this residence consisted of two affected areas. The garden area, comprised of 851 square feet of affected material, and the area behind the backyard fence, comprised of 2,610 square feet of affected material.

The excavation of soil/retort material at the Bennet Street residence was initiated by the removal of all personal belongings and vegetation in the garden area. The garden area was populated with a variety of vegetation and plants including various objects of personal belonging (firewood, bikes, etc.). Prior to excavation, the contractor prepared an inventory list of all personal belongings located m the affected area. All personal belongings in the affected area requiring removal for excavation were removed from the affected area and replaced upon the completion of excavation and backfilling. All belongings were removed manually by contractor employees and staged in the driveway area. Excavation in this area was performed using hand labor and shovels. The slag/retort material was excavated in 6 inch lifts to be inspected by the on site TNRCC representative to determine the depth of contamination. The affected material was excavated to a depth of 5 inches. Upon completion of the excavation, the base of the excavation was inspected by the TNRCC representative and visually determined to be free of contaminants. All excavated soil was manually removed with wheelbarrows and placed in roll-off boxes provided by the contractor for sampling and waste characterization at the City of Dumas Landfill, as per agreement with the City of Dumas. A total of 18 cubic yards of slag/retort material was removed from the garden area. Upon completion of the excavation activities, samples were collected from the base of the excavation and submitted to a laboratory for analytical analysis and the results indicated 8 ppm and 33 ppm Arsenic, <5 ppm and <5 ppm Cadmium, <5 and 22 ppm Lead and 46 ppm and 1,300 ppm Zinc.

Upon completion of the excavation activities and confirmation of cleanliness from the analytical results, the garden area was backfilled with 19 cubic yards of 1.5 inch unwashed gravel and compacted import clean fill material. All vegetation and personal belongings removed from the excavated area were replaced in the same location prior to remedial activities. Upon completion of the excavation activities, the garden area was inspected by the on site TNRCC representative and property owner. It was agreed that no further remedial action would be performed in this area.

The Bennett Street residence also consisted of the excavation of contaminated soil/retort material behind the backyard fence. The contaminated soil/retort material in this area was removed using a backhoe and hand labor. The excavated soil/retort material was removed in 6 inch lifts and inspected by the on site TNRCC representative to determine the depth of contamination. Upon completion of the excavation, the base of the excavation was inspected by the TNRCC representative and visually determined to be free of contaminants. The affected material was excavated to a depth of 3 inches. A total of 20 cubic yards of slag/retort material was removed from the excavation. All excavated slag/retort material was placed in roll-off boxes provided by the contractor and staged at the City of Dumas Landfill, as per agreement with the City of Dumas, for sampling and waste characterization. Samples were collected from the base of the excavation and submitted for analytical analysis and the results indicated 23 ppm Arsenic, <5 ppm Cadmium, <5 ppm Lead and 290 ppm Zinc.

Upon completion of the excavation, the excavated area was backfilled with 20 cubic yards of 1.5 inch unwashed gravel. The backfilled area was inspected by the on site TNRCC representative property owner. It was agreed that no further remedial action was required at this location.

Community Profile

The American Zinc Proposed State Superfund site is located approximately six miles northeast of the town of Dumas in Moore County, Texas. Dumas is located 50 miles north of Amarillo, in the Upper Plains of the Texas Panhandle. The 1994-95 Texas Almanac list the population of Dumas at 13,065 and all of Moore County at 18,567.
According to the 1990 U.S. Census Statistics Moore County ethnicity is: white, 71.6%; black, 0.5%, Native American 0.7%, Asian, 1.6%; Hispanic, 31.9%; and other ethnicities at 25.6%.

Extensive cattle production, feedlot operations, varied agriculture activities and the production of oil and natural gas are the main commercial interests of Moore County.

Community Involvement and Concerns

The TNRCC held a public meeting, on November 16, 1993, at Dumas City Hall, regarding the proposed listing of the American Zinc facility on the State Superfund Registry. Between forty and fifty citizens attended the November 1993 public meeting on the proposed listing.

Citizens, at that meeting, expressed concern regarding possible leaching of contaminants into the Ogallala Aquifer.

On May 26, 1994, the TNRCC held an informal information-gathering session at Dumas City Hall to conduct a survey of area residents who may have removed materials or slag, or have knowledge of such removal from the American Zinc site. Less than ten residents attended the session.

In June 1994 the TNRCC and Texas Department of Health (TDH) ran ads in the *Moore County Press* advising residents of the agency's plan to be in the Dumas area the week of July 11, 1994, to conduct additional sampling of private property that may had slag or other materials placed on it from the American Zinc site.

During the August 1997, TNRCC staff met with the owners of the four properties, that were deemed by the Texas Department of Health, to be in need of slag/retort removal. All owner signed an agreement with the TNRCC to allow the material to be removed from their properties.

The removals took place in October and November 1997.

Specific Objectives of the Community Relations Program

A. Maintain open communications between the Texas Natural Resource Conservation Commission, Moore County and State officials and concerned citizens.

B. Continue to expand the mailing list to include additional agencies, organizations, and residents that are interested in the project.

C. Provide a central information contact from whom interested parties can receive information on site activities, project status, and study results.

D. Provide all information, especially technical findings, in a language that is understandable to the general public and in a form useful to interested citizens and elected officials through the preparation of fact sheets and news releases, when major findings become available during project phases.

E. Monitor community concerns and information requirements as the project progresses by monitoring the community response to news releases and community meetings.

F. Modify the community relations plan as changes in community attitudes and needs occur and maintain accuracy during different project phases.

Community Relations Techniques

A. Project Status Briefings for community groups and concerned citizens (may include public meetings, if needed) - To periodically inform the general community of significant project developments and findings; to respond to inquiries accordingly and incorporate local concerns into the decision making process as appropriate.

B. Project Mailing List - To provide the means through which press releases, project status reports and other significant communications can be distributed to concerned groups and individuals.

C. Public Consultations - To conduct informal meetings (if needed) with residents. To provide an opportunity for affected residents to express any concerns and to make inquiries to insure effective two-way communication.

D. Program Document Repositories - To maintain easily accessible repositories through which the public may review project outputs. The public will be periodically informed of the availability of project documents and the location of repositories via techniques A through C.

E. TNRCC State Superfund Internet Homepage - provide current, timely information on state Superfund activities on the World Wide Web at the following web address: www.tnrcc.state.tx.us/waste/superfund.

F. Revise CRP - To reflect changes in site activities or local concerns. After the Proposed Remedial Action Document (PRAD) has been issued, the CRP will be revised to address implementation of the selected remedial action alternative.

Area Elected Officials

State

The Honorable Teel Bivins
Texas Senate
PO Box 9155
Amarillo, Texas 79105
806/374-8994

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