Human health and oil and gas development: A review of the peer-reviewed literature and assessment of applicability to the City of Los Angeles

Seth B.C. Shonkoff, PhD, MPH[1,2,3], Lee Ann L. Hill, MPH[1]

[1] PSE Healthy Energy, Oakland, CA
[2] Department of Environmental Science, Policy, Management, University of California – Berkeley, Berkeley, CA
[3] Lawrence Berkeley National Laboratory, Berkeley, CA

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List of Abbreviations

ALL	acute lymphocytic leukemia
CARB	California Air Resources Board
CCST	California Council on Science and Technology
CI	confidence interval
COGCC	Colorado Oil and Gas Conservation Commission
CRS	chronic rhinosinusitis
DOGGR	Division of Oil, Gas and Geothermal Resources
EOR	enhanced oil recovery
FCR	finding, conclusion, and recommendation
H_2S	hydrogen sulfide
HAP	hazardous air pollutant
HI	hazard index
LACDPH	Los Angeles County Department of Public Health
LBW	low birth weight
LOD	limit of detection
mmHg	milligrams of mercury
NHL	non-Hodgkin lymphoma
NMHC	non-methane hydrocarbon
NMVOCs	non-methane volatile organic compounds
OR	odds ratio
PAH	polycyclic aromatic hydrocarbon
SB 4	Senate Bill 4
SCAQMD	South Coast Air Quality Management District
SGA	small for gestational age
SNAPS	Study of Neighborhood Air near Petroleum Sources

SOx	sulfur oxides
TAC	toxic air contaminants
ROGER	PSE Healthy Energy Repository for Oil and Gas Energy Research
UNGD	unconventional natural gas development
US EPA	United States Environmental Protection Agency
VOC	volatile organic compound

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About PSE Healthy Energy

Physicians, Scientists, and Engineers for Healthy Energy (PSE) is a multidisciplinary, non-profit research institute that studies the way energy production and use impact public health and the environment. We share our work and translate complex science for all audiences. Our headquarters is located in Oakland, California.

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1.0. Executive Summary

An April 2017 motion from City of Los Angeles council member Wesson directed the Petroleum Administrator to work with the Los Angeles County Department of Public Health and other agencies to assess the health effects of oil and gas production in the City of Los Angeles. Physicians, Scientists and Engineers for Healthy Energy (PSE) was retained by the Office of Petroleum and Natural Gas Administration and Safety in the City of Los Angeles to conduct a review of the peer-reviewed literature focused on public health and oil and gas development and assess the applicability of this body of literature to the context of the City of Los Angeles. This study incorporates the findings contained in the public health sections of the California Council on Science and Technology Senate Bill 4 Independent Scientific Study (CCST, 2015) and incorporates a review of the peer-reviewed literature published since 2015.

For studies published since 2015, in this assessment we focus primarily on two broad categories of studies: (1) studies of human health hazards, risks and impacts in the context of air pollution from upstream oil and gas development; and (2) human health hazards, risks and impacts as a function of distance from and density of upstream oil and gas development. A single peer-reviewed oil and gas development and health study focused in California has been published to date. There are however a variety of results and conclusions drawn from the greater peer-reviewed literature outside of California that are applicable in many ways to the City of Los Angeles context. From the findings of this assessment, we compiled the following findings, conclusions and research and policy recommendations (FCR):

FCR-1: Conduct studies in the State of California to assess the relationship between oil and gas development and public health as a function of distance.

Finding: Only one peer-reviewed oil and gas development and health study has been conducted in the State of California. There are however a variety of results and conclusions drawn from the greater peer-reviewed literature outside of California that are applicable to the California context.

Conclusion: There is a dearth of peer-reviewed studies on oil and gas development that are specific to the State of California and the City of Los Angeles, yet there are results and conclusions drawn from the weight of the peer-reviewed literature outside of California that are relevant to the California context.

Recommendations:

(1) Conduct health studies in the City of Los Angeles on the health dimensions of oil and gas development as a function of distance and oil and gas well density that incorporate multiple potential environmental and exposure pathways. These studies should assess active oil and gas development and could also include inactive oil and gas development such as plugged and abandoned wells and associated infrastructure. Given the increasingly expansive body of

health literature on the topic, consider promulgating health-protective policies based on the existing literature.

(2) Ensure that field-based air pollution monitoring at the community scale and in close proximity to oil and gas development continues and expands and that it is implemented in ways that properly characterize emissions from these processes. This includes but is not limited to ensuring that air monitoring methods are deployed to capture the intermittent and periodic nature of emission events throughout the oil and gas development process and that there is access to well pad-level activity information to inform the monitoring approaches.

FCR-2: Consider the implementation of a minimum surface setback requirement, caps on oil and gas development density and deployment of increased emission control strategies in the City of Los Angeles.

Finding: The majority of peer-reviewed studies that assess human health in the context of oil and gas development as a function of distance and density have noted increased hazards, risks and health impacts as distance decreases and density increases. The density of oil and gas development in oil and gas-producing neighborhoods in and near the City of Los Angeles is as high or higher than densities of oil and gas development associated with health impacts in out of state studies.

Conclusion: The development of oil and gas close to human populations poses higher risks of exposure to health-damaging air pollutants than the development of oil and gas further away from human populations. The same trend tends to exist for higher vs. lower density of oil and gas development.

Recommendations:

(1) Agencies with jurisdiction should consider the implementation of minimum surface setbacks between oil and gas development and sensitive receptors including but not limited to residences, schools, daycare centers and hospitals in the City of Los Angeles. The decision as to how large the setback is should also take the available body of epidemiological studies on oil and gas development into account. Studies to date conducted in regions with migrated hydrocarbon reservoirs have found associations with increased health risks associated with oil and gas development ranging from approximately 0.1 miles (500 feet) to one mile (5,290 feet). As such, a setback greater than 500 feet and up to 5,290 feet should be considered.

(2) Given that the *density* of oil and gas development has been found across a number of health studies to be associated with increased health risks, agencies with jurisdiction may consider limiting the density of wells and other oil and gas development infrastructure at oil and gas producing areas within and near the City of Los Angeles.

(3) Best available emission control technologies and management approaches should be deployed on all oil and gas wells and ancillary infrastructure to limit emissions of health-damaging air pollutants. Target air pollutants should include both those that are regularly monitored for (e.g., Criteria Air Pollutants, Toxic Air Contaminants and aromatic hydrocarbons such as benzene)

as well as those pollutants that are less frequently monitored for including, but not limited to chemicals reported to SCAQMD pursuant to Rule 1148.2 that are known air pollutants.

2.0. Introduction

The City of Los Angeles is a global megacity where intensive oil development occurs in close proximity to large urban populations. This co-occurrence of dense oil and gas activities and human populations poses potential human health hazards, risks and impacts that may be less present in areas of lower population density. Pursuant to California Senate Bill 4 (Pavley, 2013) (SB 4), the California Council on Science and Technology (CCST) conducted an independent scientific assessment of well stimulation in California with chapters focused on potential hazards and risks of well stimulation (e.g. hydraulic fracturing) and oil and gas development in general (CCST, 2015). Within this report were two health assessments: one focused on human health and oil and gas development across the state (Shonkoff et al., 2015a) and a human health case study specific to the Los Angeles Basin (Shonkoff et al., 2015b). These human health assessments provided a review of the peer-reviewed literature on oil and gas development and human health hazards, risks and impacts published between 2009 to 2014. Since the CCST SB 4 Report (2015), numerous additional studies focusing on oil and gas development and human health have been published. In this report we review the public health findings presented in the CCST SB 4 Report (Shonkoff et al., 2015a; Shonkoff et al., 2015b) and then summarize the findings of the peer-reviewed literature on oil, gas and health published since then (2015 - 2018), with a particular focus on health outcome studies and studies that have an air pollution focus. We then evaluate this body of literature in the context of oil and gas development in the Los Angeles Basin and where possible in the City of Los Angeles in particular.

2.1. Our approach to hazard and risk

The terms *hazard* and *risk*, while often used interchangeably, have different implications in the field of risk assessment. A *hazard* is defined as any biological, chemical, mechanical, environmental, or physical stressor that is reasonably likely to cause harm or damage to humans, other organisms, the environment, and/or engineered systems in the absence of control (Sperber, 2001). *Risk* is the probability that a given hazard plays out in a scenario that causes a particular harm, loss, or damage (National Research Council, 2009). Determining risk, or the probability of harm, requires a receptor (e.g., human population) to be exposed to the hazard, and often depends on the vulnerability of the population (e.g., age, pre-existing conditions) (Shonkoff et al., 2015a). Living in close proximity to oil and gas development may increase the likelihood of populations to come into contact with various hazards, including air pollutants.

2.2. Impetus for this report

An April 2017 motion from City of Los Angeles council member Wesson directed the Petroleum Administrator to work with the Los Angeles County Department of Public Health and other agencies to assess the health effects of oil and gas production in the City of Los Angeles. Physicians, Scientists and Engineers for Healthy Energy (PSE) was retained by the Office of Petroleum and Natural Gas Administration and Safety in the City of Los Angeles to conduct a review of the peer-reviewed literature focused on public health and oil and gas development and assess the applicability of this body of literature to the context of the City of Los Angeles.

2.3. Focus of this review: local air pollution and health dimensions of oil and gas development

In this report we review the findings from the CCST SB 4 Report (2015) and synthesize the available peer-reviewed literature on oil and gas development, air quality and human health that has been published since. We finalize our assessment with a discussion of the applicability of this body of peer-reviewed literature to the context of oil and gas development and human health in the City of Los Angeles and provide conclusions and recommendations.

3.0. Approach

In alignment with the approach of the health assessments in the CCST SB 4 Report (Shonkoff et al., 2015a and Shonkoff et al., 2015b), in this report we employ a top-down assessment to evaluate hazards associated with *upstream* oil and gas development by starting with population health outcomes and working backwards to evaluate potential associations between health outcomes and oil and gas development activity. Upstream activities include the transport of equipment and materials to and from the well pad; well drilling, mixing, handling, and injection of oil and gas chemicals; and management of recovered fluids/produced water, drill cuttings, and other waste products (Adgate et al., 2014; Johnston et al., 2019; NRC, 2014; Shonkoff et al., 2014). Sources of air pollutants include products of incomplete combustion and chemicals emitted directly and indirectly from surface and subsurface equipment including, but not limited to, wells, pumps, generators, compressors, pneumatic devices, storage and separator tanks, surface impoundments, solid and liquid waste handling and from venting and flaring of gases. Air pollutant emissions from upstream oil and gas development can include toxic air contaminants (TACs), criteria pollutants, and reactive organic gases which are associated with the formation of tropospheric ozone (i.e., smog).

Please note that air pollution and health impacts associated with midstream emissions (e.g., transmission pipelines and underground gas storage) and downstream emissions (e.g. emissions from refining and use of hydrocarbon products) were not considered in the CCST SB 4 Report (2015) or in this report. To apply this top-down approach, we draw from the peer-reviewed literature, where health hazards, risks and impacts of upstream oil and gas development are studied.

3.1. Study Inclusion Criteria and Approach

We extracted peer-reviewed studies published prior to 2015 that focus on air pollution, public health, and oil and gas development from the CCST SB 4 Report (2015). Peer-reviewed studies that were published prior to 2015 but were not discussed in the CCST SB 4 Report (2015) were beyond the scope of this review; however, we do note that there were approximately 25 health and 25 air quality original research studies published prior to 2015 (Shonkoff et al., 2015c). Four key studies discussed within the CCST SB 4 Report (2015) are included in Section 4.3.

We then searched scientific publication databases (Web of Science, PubMed and Google Scholar) using search terms (oilfield, oil field, oil drilling, oil and gas, natural gas, oil development, and gas development) AND (health, epidemiology, risk, hazard, air pollution, air quality) for *peer-reviewed* journal articles published after January 1, 2015. Finally, we extracted studies published between 2015 and 2018 from the PSE Healthy Energy Repository for Oil and Gas Energy Research (ROGER)[1], a near-exhaustive database of peer-reviewed literature on the impacts of shale and tight gas as well as other types oil and gas development (PSE Healthy Energy, 2018). Studies housed in ROGER are classified by impact category (e.g. climate, air quality, water quality, health, etc.). We conducted our last publication search on December 16th, 2018. Studies from the health and air quality impact categories were evaluated for inclusion in this assessment.

We included studies if they examined health hazards, risks, or impacts associated with air pollutants from upstream oil and gas activities in North America and were published in English. Government reports, environmental impact statements, white papers, law review articles, and other grey literature are not included in this assessment. Occupational health studies, while important, were outside the scope of this assessment and are not discussed explicitly. Air pollution studies were excluded if they lacked in-situ air quality measurements (e.g., studies that estimate emissions, but not impacts on air quality), examined regional rather than local air quality, or did not examine air pollution and exposure at specified distances.

Furthermore, health studies focused on factors of perception, subjective well-being, and mental health were not included (e.g., Hirsch et al., 2018; Maguire & Winters, 2017). The health literature also includes studies focused on other environmental stressors associated with oil and gas development, such as noise and light pollution and chemical exposure pathways through water. A relatively inclusive summary of this body of literature can be found in Hays and Shonkoff (2016). These studies were also outside of the scope of this review. We identified five studies focused on air pollution and health and 19 studies focused on public health outcomes published between 2015 and 2018 for inclusion in this assessment (Section 4.4, Figure 2).

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[1] PSE Repository of Oil and Gas Energy Research (ROGER) Database can be accessed at: https://www.psehealthyenergy.org/our-work/shale-gas-research-library/.

3.2. Approach to Calibration of Studies to City of Los Angeles Context

While there continues to be a dearth of epidemiological and other health investigations on oil and gas development in the State of California in general and the Los Angeles Basin in particular, an increasing number of these types of studies have assessed the health dimensions of oil and gas development in other parts of the United States and Canada. Each of the studies discussed in this review – as with any scientific study – has strengths and limitations in terms of study design, geographic focus, and causal inference. Some of the studies to date focus on shale gas and tight oil development enabled by high-volume hydraulic fracturing, which with few exceptions has not been deployed in the State of California and the Los Angeles Basin in particular. However, many of the studies published since January 2015 are relevant to the California and City of Los Angeles contexts given similar petroleum geology (e.g., migrated oil), technological approach to oil and gas production (e.g., enhanced oil recovery and other types of hydrocarbon production of migrated oil accumulations), density of oil and gas development, regulatory requirements (e.g., methane and non-methane volatile organic compound emission control rules), and maturity of oil and gas fields (e.g., presence of gas-gathering infrastructure and pipeline networks for water and hydrocarbon conveyance to reduce the need for trucking).

To further calibrate the results of the out of state studies to the City of Los Angeles context, we evaluated the human health hazards of chemical use in upstream oil and gas development as reported to South Coast Air Quality Management District (SCAQMD) pursuant to Rule 1148.2. This analysis can be found in the chemical assessment (Shonkoff et al., 2019b) in this larger report from the Office of Petroleum and Natural Gas Administration and Safety.

4.0. Review of the peer-reviewed literature on air pollution, human health, and oil and gas development

The results of our review of the literature are presented in the following sections:

1. **Summary of key public health findings from the CCST SB 4 Report (2015):** We review the key air quality and public health conclusions and recommendations from the CCST SB 4 Report (CCST, 2015).
2. **Studies that met our inclusion criteria for this review of the literature (2015 – 2018):** We depict the number of studies identified, screened, excluded, and included in this assessment.
3. **Review of air pollution and public health studies:** We summarize the peer-reviewed literature focused on air pollution associated with oil and gas development and health. These studies typically include local air monitoring efforts that contextualize findings in terms of human health hazard and risk through comparison of observed air pollution concentrations with health-based air quality reference concentrations and other standards.

4. **Review of public health outcome and epidemiological studies:** We summarize epidemiological research that estimates exposure using proximity to (or distance from) oil and gas development. Exposure metrics used in these studies often consider well density, temporally- and geographically-explicit well pad activities, and well productivity. While our primary focus is on studies that measure local-level exposures (e.g. by residence), studies that address exposures at a higher level (e.g. by zip code, county) are also discussed.
5. **Setback distance summary:** Peer-reviewed studies that discuss setback distances from oil and gas development are discussed. Existing setback distances in California and other states and localities are also presented.

4.1. Summary of key public health findings in the CCST SB 4 Report (2015)

The CCST SB 4 Report (2015) characterized emissions associated with oil and gas development in California, quantified populations in proximity to oil and gas development in California, summarized the environmental public health literature, and made an effort to calibrate findings from out-of-state studies to the California context. Direct and indirect impacts to air quality and human health were considered. The key principles, conclusions, and recommendations from the CCST SB 4 Report (2015) related to air quality and public health are presented verbatim in Table 1.

While the CCST SB 4 Report (2015) focused largely on issues of well stimulation (e.g. hydraulic fracturing, matrix acidizing and acid fracturing), a significant overarching conclusion of the report was that the majority of impacts associated with well stimulation are attributable to impacts of oil and gas development more generally. For example, air pollutants – such as benzene – may be emitted to the atmosphere during the relatively brief amount of time that hydraulic fracturing takes place, but emissions also occur, often in higher mass and rate during other phases of oil and gas development. Moreover, while benzene is sometimes reported as used as an additive in hydraulic fracturing fluids, emissions of benzene occur throughout the oil and gas development process due to the fact that the compound is co-produced with oil and gas and so the technological approach to hydrocarbon extraction – be it via hydraulic fracturing, steam injection or waterflooding – may not be as important from a toxic air pollutant exposure perspective.

Table 1. Principles, conclusions, and recommendations from the CCST SB 4 Report (2015) that consider air quality and public health.

Principle	Conclusion	Recommendation
Account for and manage both direct and indirect impacts of hydraulic fracturing and acid stimulation.	The majority of impacts associated with hydraulic fracturing are caused by the indirect impacts of oil and gas production enabled by the hydraulic fracturing.	Evaluate impacts of production for all oil and gas development, rather than just the portion of production enabled by well stimulation.
Understand and control emissions and their impact on environmental and human health.	Air pollutants and toxic air emissions[2] from hydraulic fracturing are mostly a small part of total emissions, but pollutants can be concentrated near production wells.	Control toxic air emissions from oil and gas production wells and measure their concentrations near production wells: Apply reduced-air-emission completion technologies to production wells, including stimulated wells, to limit direct emissions of air pollutants, as planned. Reassess opportunities for emission controls in general oil and gas operations to limit emissions. Improve specificity of inventories to allow better understanding of oil and gas emissions sources. Conduct studies to improve our understanding of toxics concentrations near stimulated and un-stimulated wells
	Emissions concentrated near all oil and gas production could present health hazards to nearby communities in California.	Assess public health near oil and gas production: Conduct studies in California to assess public health as a function of proximity to all oil and gas development, not just stimulated wells, and develop policies such as science-based surface setbacks, to limit exposures.

4.2. Summary of toxic air contaminant findings in the Los Angeles Basin from the CCST SB 4 Report (2015)

Emissions of benzene and other toxic air contaminants (TACs) present well understood health hazards. Many TACs are co-produced with oil and gas development because of their natural occurrence in oil and gas reservoirs, regardless of whether hydraulic fracturing and other forms of well-stimulation are used (Garcia-Gonzales et al., 2019a). A previous assessment of California emissions inventories suggest that the upstream oil and gas development sector is likely

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[2] Toxic air pollutants, also known as hazardous air pollutants, are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects. Criteria air contaminants (CAC), or criteria pollutants, are a set of air pollutants that cause smog, acid rain, and other health hazards (CCST, 2015).

responsible for a small fraction (<1%) of all criteria pollutants emitted in the South Coast Region of California (including Los Angeles), as this region is known for significant and diverse sources of emissions from mobile (cars, trucks and other transportation) and other industrial sources (Shonkoff et al., 2015b). However, as of 2014, emissions reported to emissions inventories suggest that 2,361 kg/year of benzene is emitted by the stationary components of upstream oil and gas development in the Los Angeles Basin, accounting for 9.6% of benzene emissions and 3.8% of formaldehyde emissions from all Los Angeles Basin *stationary* sources (Shonkoff et al. 2015b) (Table 2).

Benzene and formaldehyde emissions from oil and gas development represented a much smaller proportion (0.14% and 0.25%, respectively) of benzene emissions from *all* Los Angeles Basin sources (including mobile sources) due to the fact that the mobile sector is the predominant contributor of benzene emissions (Shonkoff et al. 2015b). Smaller proportions of other TAC species were identified (Table 2).

The proportion of reported TACs – with the exception of benzene and to a lesser extent, formaldehyde – attributable to upstream oil and gas development in the Los Angeles Basin has been reported as low. However, basin-wide fractions of emissions are less meaningful from a public health perspective than the mass of pollutants emitted, the timing and duration of emissions, and the geographic location of and proximity to human populations where emissions occur. While the spatial distribution of TAC emissions across Los Angeles oil and gas facilities are not known, what is known is that emissions of these TACs and other air pollutants from oil and gas development in the Los Angeles Basin occur in close proximity to human populations, including sensitive receptors such as schools, daycare centers, hospitals and elderly care facilities. Populations in close proximity to oil and gas development may be disproportionately exposed to associated emissions.

Table 2. Contribution of upstream oil and gas sources to TAC emissions in South Coast Region (kg/y) in 2010.

	Stationary oil and gas sources (kg/y) (2012)	Fraction of emissions from stationary sources	Emissions from all stationary and mobile sources (kg/y) (2010)	Fraction of all emissions from all sources (kg/y) (stationary and mobile)
1,3-Butadiene	56	1.60%	382,307	0.01%
Acetaldehyde	1	0.00%	1,552,128	0.00%
Benzene	2,361	9.60%	1,659,155	0.14%
Carbonyl sulfide	not available	not available	20	not available
Ethyl Benzene	28	0.50%	1,000,213	0.00%
Formaldehyde	5,846	3.80%	2,375,149	0.25%
Hexane	1	0.00%	1,608,302	0.00%
Hydrogen Sulfide	not available	not available	6,238	not available
Toluene	1	0.00%	6,860,168	0.00%
Xylenes (mixed)	1	0.00%	1,275,480	0.00%

Source: Shonkoff et al. (2015b)

As of 2015, in the Los Angeles Basin alone, approximately nearly 630,000 residents, 130 schools, 213 elderly facilities and 184 daycare facilities were sited, within a half-mile (2,625 ft) of an active oil and gas well. Of note, more than 32,000 people in the Los Angeles Basin are estimated to live within 100 meters (m) (328 ft) of an active oil and gas well (Shonkoff et al., 2015b) (Table 3).

Table 3. Numbers of residents and other sensitive receptors within various proximities of active oil and gas wells.

Buffer Distance (ft)	Buffer Distance (m)	Number of residents	Number of Schools	Number of Children Attending Schools	Number of Elderly Facilities	Number of Daycare Facilities	Under 5	Over 75
328	100	32,071	4	3,270	12	5	2,295	1,664
1,312	400	233,102	50	34,819	94	72	16,685	14,005
2,625	800	627,546	130	89,241	213	184	4,050	35,189
3,281	1,000	866,299	180	135,797	258	262	62,547	47,759
5,249	1,600	1,677,594	348	242,833	429	524	122,321	91,452
6,562	2,000	2,257,933	470	332,855	582	718	164,992	122,737

Source: Adapted from Shonkoff et al. (2015b)

Many in-situ monitoring and modeling studies estimate that emissions of health-damaging air pollutant species can be episodically elevated, leading to degraded air quality in proximity to and downwind from oil and gas development operations. For instance, Brown et al. (2015) modeled exposures between one and two kilometers (km) (3,281 - 6,562 ft) downwind of unconventional natural gas development and noted the variability across oil and gas development (shale gas development) phases by time (Figure 1). Brown et al. (2015) focused on shale gas and of course the development of this unconventional resource differs in many ways from the production of more shallow migrated oil and gas such as what occurs in the Los Angeles Basin. However, much of the infrastructure deployed for such activities are similar. All of the categories visualized below in Figure 1– flaring/finishing/compressor stations, and ongoing oil and gas production – are used in the Los Angeles Basin with often the exception of hydraulic fracturing, which is only used on a very limited basis in a small proportion of wells (Shonkoff et al., 2015b; DOGGR, 2019).

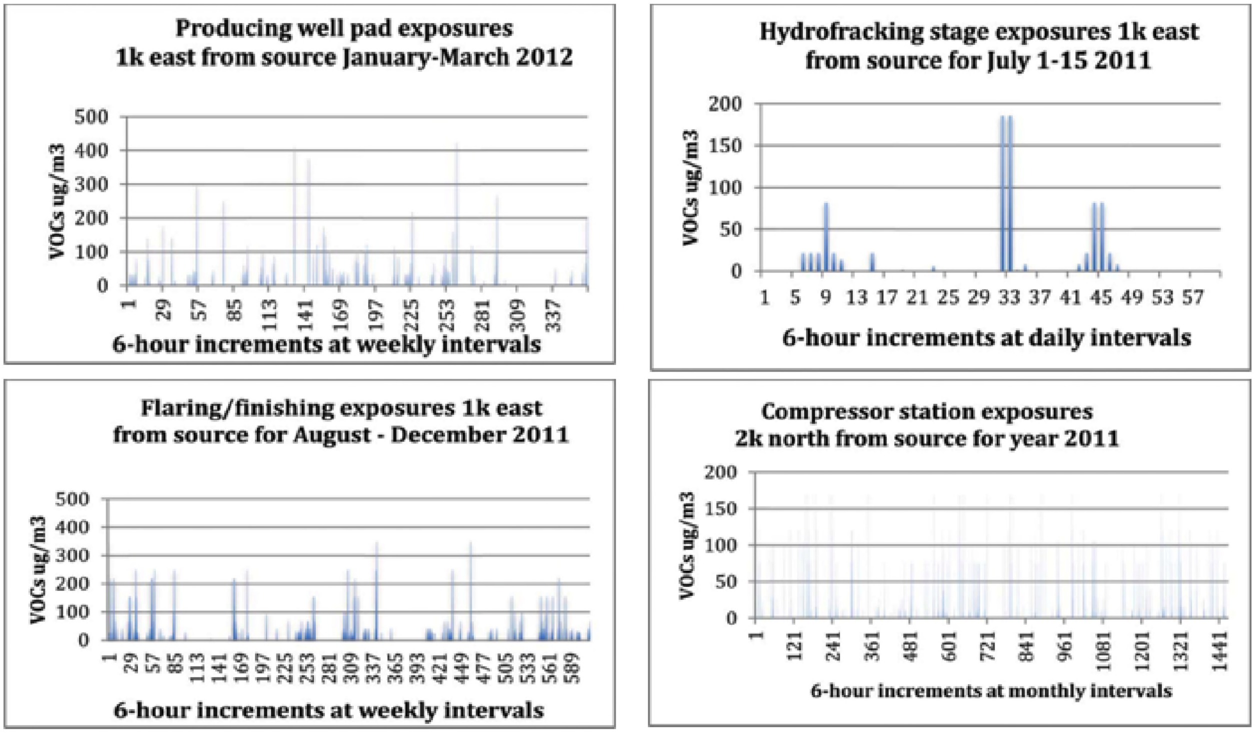


Figure 1. Intermittent spikes in volatile organic compounds (VOCs) during oil and gas development activities.

Source: Brown et al. (2015)

Many of constituents associated with oil and gas development can damage human health and place disproportionate risks on sensitive populations (e.g. children, pregnant women, the elderly) if they have significant enough exposures. Using California state emission inventories, Shonkoff et al. (2015b) found that oil and gas production in the San Joaquin Valley air district likely accounts for significant emissions of sulfur oxides (SOx), TACs such as benzene and hydrogen sulfide (H_2S). Oil and gas development accounted for a smaller proportion of total emissions in the Los Angeles

Basin (Table 2); however, larger and denser populations live, work, play and learn within close proximity of oil and gas development in this region, increasing the *intake fraction* of emissions that do occur.

The intake fraction is defined as the ratio of the mass of a pollutant inhaled or ingested to the mass of the pollutant emitted. As such, in the case of emissions of most pollutants to the air, intake fraction is the proportion of the total air pollutants emitted that are taken into the lungs of a human. The closer people are to oil and gas activities, the higher their potential exposure to air pollutants emitted from these facilities and the higher their risk of associated health effects and the larger the population, the larger the intake fraction. For a more in-depth discussion of intake fraction and its relevance to the South Coast region of California, please see Shonkoff et al. 2015b.

4.3. Summary of local air pollution and health studies and health outcome studies from the CCST SB 4 Report (2015)

Four key peer-reviewed studies were discussed in the CCST SB 4 Report (2015) regarding local air pollution and health or health outcomes associated with oil and gas activities. Considering community-level exposures, McKenzie et al. (2012) conducted air monitoring near oil and gas activities and proximal populations in Colorado. Using United States Environmental Protection Agency (US EPA) guidance to estimate chronic and sub-chronic non-cancer hazard indices (HIs) as well as cancer risks, the authors found that those living in closer geographical proximity to active oil and gas wells (≤ 2,640 ft) were at an increased risk of acute and sub-chronic respiratory, neurological, and reproductive health effects. Increased risk was driven primarily by exposure to trimethylbenzenes, xylenes, and aliphatic hydrocarbons; slightly elevated excess lifetime cancer risk estimates were also driven by benzene and aliphatic hydrocarbon exposure (McKenzie et al., 2012).

The findings of McKenzie et al. (2012) are in line with assumptions and calculations of atmospheric dilution data of conserved pollutants by the US EPA (1992). In 1992 the US EPA published a study on screening procedures for estimating the air quality impact of stationary sources. Using their assumptions, dilution of conserved TACs, such as benzene at 800 m (2,640 ft) is on the order of 0.1 mg/m^3 per g/s (US EPA, 1992). At 2,000 m (6,562 ft), dilution increases to 0.015 mg/m^3 per g/s and 0.007 mg/m^3 per g/s at 3,000 m (9,843 ft). Given that benzene poses an increased risk at a dilution of 0.1 mg/m^3 (estimated at $^1/_2$ mile, 2,640 ft), it is not certain, under these assumptions that atmospheric concentrations of benzene out to 2,000 m and 3,000 m (6,652 ft and 9,843 ft) can necessarily be considered low risk. However, beyond 3,000 m (9,843 ft), where concentrations fall more than two orders of magnitude via dilution relative to the $^1/_2$-mile radius, there is likely to be a sufficient margin of safety for a given point source. Of course, the health relevance of these estimates of atmospheric dilution strongly depend upon the mass and concentration of conserved pollutant emissions – such as benzene – that are emitted from a given stationary source.

In an oil and gas industry study in Texas, Bunch et al. (2014) compared volatile organic compound (VOC) concentration data from air monitors at six locations in the Barnett Shale with federal and state health-based air concentration values to determine possible acute and chronic health effects. The authors found that shale gas activities did not result in community-wide exposures to concentrations of VOCs at levels that would pose a health concern. Bunch et al. (2014), unlike McKenzie et al. (2012), used air quality data generated from monitors focused on *regional* atmospheric concentrations of pollutants in Texas, while McKenzie et al. (2012) included samples at the community level. Finer geographically scaled air sampling often captures local atmospheric concentrations that are more relevant to human exposure than sampling at the regional scale (Shonkoff et al., 2014). This observation may be driven by relatively steep gradients of conserved pollutants falling out of the atmosphere as they move away from their emission source.

Macey et al. (2014) analyzed air samples from locations in five different states using a community-based monitoring approach. Authors found that levels for eight volatile chemicals, including benzene, formaldehyde, hexane, and hydrogen sulfide, exceeded federal guidelines (ATSDR minimal risk levels (MRLs) (ATSDR, 2019) and US EPA Integrated Risk Information System (IRIS) cancer risk levels (USEPA 2017) in a number of instances. Self-reported data from a number of the residents who collected the samples reported a range of common health symptoms, including "headaches, dizziness or light-headedness, irritated, burning, or running nose, nausea, and sore or irritated throat" (Macey et al., 2014). The authors did not attempt to associate the reported health effects with the chemicals measured in the samples or seek verification of health symptoms by a physician. However, the study suggests that concentrations of air pollutants near oil and gas operations may be elevated to levels where health impacts could occur.

Health outcome studies published by the release of the CCST SB4 Report (2015) primarily used self-reported data as opposed to physician-reviewed and validated data (Rabinowitz et al., 2015; Steinzor et al., 2013). However, one peer-reviewed health study (McKenzie et al., 2014) is an exception to this trend. In a retrospective cohort study in Colorado, McKenzie et al. (2014) examined associations between maternal residential proximity and well density and perinatal outcomes. Risk for congenital heart defects in neonates was 30% (odds ratio [OR]: 1.3, (95% confidence interval [CI]: 1.2-1.5) greater among those born to mothers who lived in the highest density of gas development (> 125 wells per mile) compared to those with no wells within a 16 km (52,493 ft) radius of maternal residence. Babies born to mothers in the highest density of gas development had twice the odds (OR = 2.0, 95% CI: 1.0-3.9) of being born with neural tube defects than those born to mothers living with no wells within a 16-km (52,493 ft) radius (McKenzie et al., 2014). Exposure was negatively associated with preterm birth and a positive association of small magnitude was observed with fetal growth. No association was observed for oral clefts. The authors suggest that observed increased risk of neural tube defects and congenital heart disease with increasing density of gas development may be due increased atmospheric concentrations of benzene, a compound known to be associated with both of these conditions (Lupo et al., 2011). However, no air quality monitoring or field-based exposure assessment were included in this study, so the posited mechanism was not able to be directly verified.

While no peer-reviewed California-specific health studies were available for inclusion in the CCST SB 4 Report (2015), studies outside of California indicate that the most significant exposures to toxic air contaminants such as benzene, aliphatic hydrocarbons and hydrogen sulfide occur within ½ mile (2,640 ft) from active oil and gas development. Many of these compounds are co-produced from the hydrocarbon reservoir and co-emitted with oil and gas production. There is less certainty surrounding the potential for and impact of exposures to chemicals used for well stimulation and routine oil and gas development activities such as wellbore cleanouts, drilling, and routine well maintenance, further emphasizing the need to examine air quality and health risks associated with oil and gas development generally and not specifically around wells that have been hydraulically fractured.

4.4. Number of studies that met our inclusion criteria for this review of the literature published between 2015 – 2018

In the approach section of this report, we described our criteria for inclusion of studies published between 2015 and 2018 for further assessment in this report. In Figure 2 below, we show the numbers of studies that we initially found using our keywords across the study databases we searched and the number of studies that met our inclusion criteria and ended up included in this review. In the end, there were 24 peer-reviewed studies that met our criteria and were included in this study. We also included more studies on noise and oil and gas development, but these are separate from our systematic literature review on studies focused on air pollution and distance from and density of oil and gas development and public health.

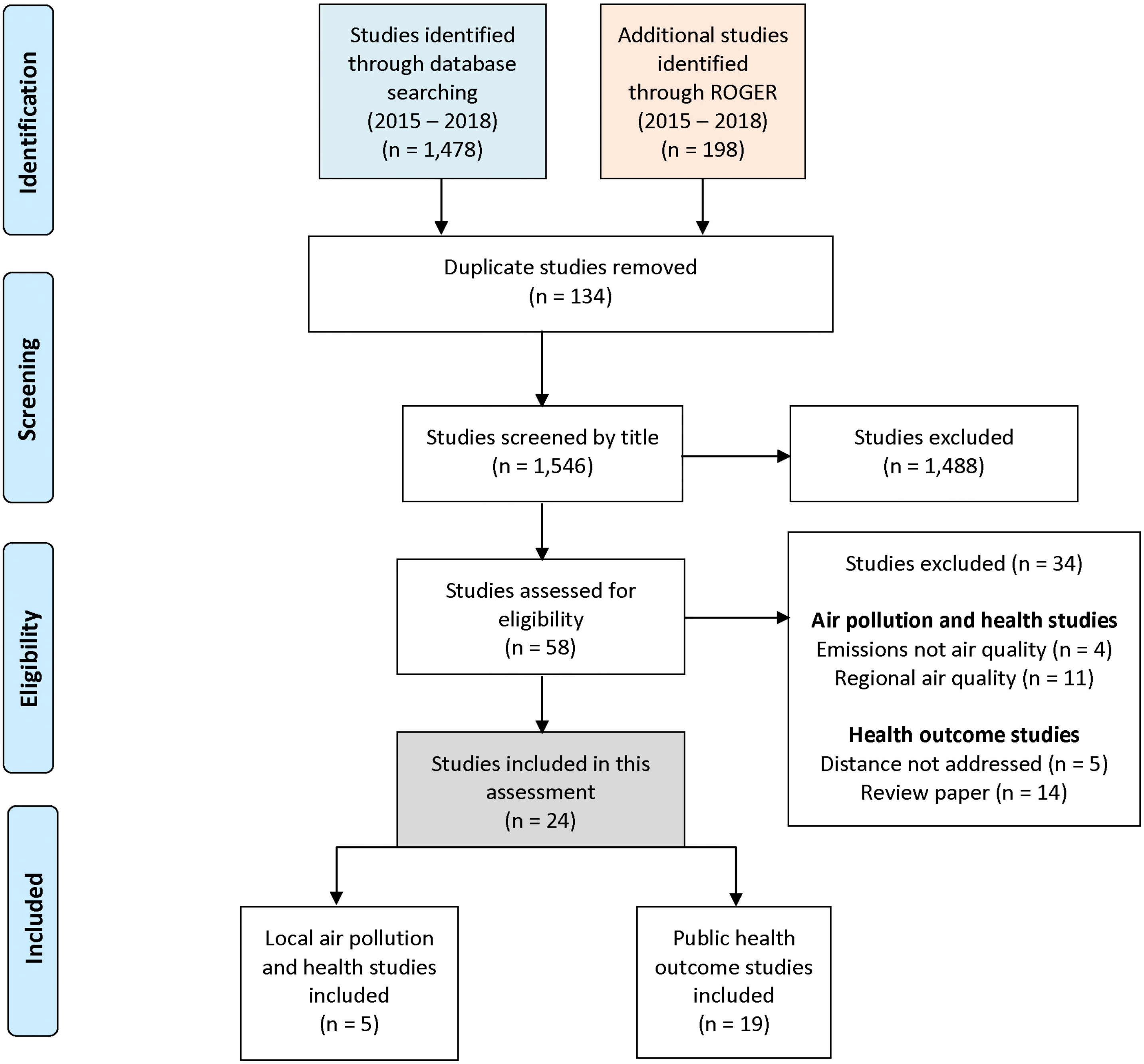


Figure 2. Decision tree to select studies that met our inclusion criteria for this 2015 – 2018 review.

4.5. Review of studies that investigate air pollution and distance from and density of oil and gas development and public health

As noted in the previous section, air pollution attributable to oil and gas development and its associated hazards and risks were evaluated in the CCST SB 4 Report (2015). In this section we discuss the peer-reviewed literature focused on local air pollution associated with upstream oil and gas development activities and published since 2015. Upstream activities include the transport of equipment and materials to and from the well pad; mixing, handling, and injection of oil and gas chemicals; and management of recovered fluids/produced water, drill cuttings, and other waste products (Johnston et al., 2019; Adgate et al., 2014; NRC, 2014). Sources of air pollutants include products of incomplete combustion and chemicals emitted directly and indirectly from surface and subsurface equipment including, but not limited to, wells, pumps, generators, compressors, pneumatic devices, storage and separator tanks, surface impoundments, solid and liquid waste handling and from venting and flaring of gases. Air pollutant emissions from upstream oil and gas development can include toxic air contaminants (TACs), criteria pollutants, and reactive organic gases which are associated with the formation of tropospheric ozone (i.e., smog). Chemicals known to be associated with oil and gas development pose acute and chronic health hazards, however health risks and impacts associated with these contaminants are dependent on the magnitude and duration of exposure.

While not always possible, in each reviewed study we note the geography, hydrocarbon resource being developed (e.g., oil or gas or both), the formation type (source rock/shale, migrated oil or gas, etc.) and the type of production technique employed (e.g., hydraulic fracturing, water flooding, steam injection, enhanced oil recovery, etc.). These specifications help to determine the applicability of a given study to the California context in general and the City of Los Angeles context in particular. Further, while practices and outcomes of each project are not available, we note the broad regulatory overlays of study location at the state level.

The environmental public health literature supports geographic proximity to active oil and gas development as an exposure and health impact risk factor. While oil and gas development contributes to regional air quality impacts (Allen, 2016; Halliday et al., 2016; Helmig, Thompson, Evans, & Park, 2014; Hildenbrand et al., 2016; Pétron et al., 2012; Pétron et al., 2014; Roy et al., 2014; Thompson et al., 2014) the majority of studies that assess air quality as a function of distance have observed that concentrations of various hazardous and other air pollutants can be even higher in close proximity to active oil and gas development (Brown et al., 2015; Brown et al., 2014; Colborn et al., 2014; Macey et al., 2014; McKenzie et al., 2012; McKenzie et al., 2018a; Rich & Orimoloye, 2016). The majority of studies that have assessed associations between oil and gas development and emissions of hazardous air pollutants (HAPs) have identified benzene, toluene, ethylbenzene and xylenes (BTEX), n-hexane, styrene, and 1,3 butadiene as emitted pollutants (Garcia-Gonzales et al., 2019a). The minority of studies, such as Bunch et al. (2014) did not find a positive correlation between proximity and air pollutant concentrations.

Intermittent spikes of emissions from oil and gas activities and equipment have also been observed (Allen, 2014; Brown et al., 2015), which may have a limited influence on regional air pollutant concentrations but are likely to be associated with increased exposures to populations in close proximity to emission sources. As such, studies that focus on regional concentrations of air pollutants associated with oil and gas development may arrive at estimates of low- to moderate-level chronic exposures experienced by regional populations, but it is important to consider the proximity of receptors to sources to capture the range of potential public health risks (McKenzie et al., 2018a; Pétron et al., 2014; Shonkoff et al., 2015b).

Five studies have been published between 2015 – 2018 that characterize local exposures to nearby oil and gas activities using in-situ air monitoring. Paulik et al. (2016) deployed 23 passive air samplers in rural Ohio for three to four weeks to quantify polycyclic aromatic hydrocarbon (PAH) concentrations by distance to an active natural gas well pad. Sites were excluded if they were near other known sources of PAHs (e.g. airports, within city boundaries). Using PAH ratios, authors determined that PAH concentrations were from primarily petrogenic sources, as opposed to sources from combustion. As observed in other studies, health risk decreased with distance. Excess lifetime cancer risks associated with exposure to PAHs at sites closest to active wells (<328 ft) were estimated at 0.04 in one million, and decreased 30% at beyond 1 mile (5,280 ft) (0.027 in a million). Lifetime cancer risks observed were below US EPA upper threshold of one case per 10,000. Of note, passive sampling methods are useful to calculate average concentrations over deployment period, but do not characterize episodic spikes in emissions.

Paulik et al. (2018) used stationary passive samplers to characterize environmental exposure in conjunction with wearable silicone wristbands to estimate individual exposure to PAHs associated with nearby natural gas activities in Ohio. Thirty passive samplers were deployed near active (n=3) and proposed (n=2) natural gas sites at 55 to 122 m (180 – 400 ft) from the edge of the well pad, and silicone wristbands were given to participants living or working near the stationary sampling sites (n=19). Total PAH summation (ΣPAH) in air was significantly higher at active natural gas sites (Wilcoxon rank sum test, $p<0.01$) and was also more petrogenic at active sites as compared to proposed sites. ΣPAH detected using wristbands was significantly higher for participants within 0.75 km (2,461 ft) of an active well as compared to participants within 2-10 km (6,562- 32,808 ft) of an active well (Wilcoxon rank sum test, $p < 0.005$). Distance from participants home or work locations to nearest active well was significantly negatively correlated with ΣPAH detected by participants wristband (Pearson's correlation- -0.76, p=0.00010). Finally, there was a significant positive correlation between ΣPAH in participants' wristbands and ΣPAH in air measured closest to participants' homes or workplaces (simple linear regression, $p < 0.0001$). This study evaluated broad environmental exposure and individual exposure to PAHs associated with active natural gas sites, and found highest exposure correlated with closer distance using stationary and personal sampling devices. Participants completed exposure logs to identify additional sources of PAH exposure (e.g., cigarette smoke). However, while homes and workplaces were used as reference locations, exact time spent at reference locations was unknown. This work suggests that active natural gas sites emit PAHs into the air, and that living or working close to these sites may increase personal exposure to PAHs.

In Washington County, Pennsylvania, Maskrey et al. (2016) monitored for VOCs for three months at two locations near a single hydraulic fracturing well pad that had already been drilled. Monitoring sites included a school 863 m (2,831 ft) away and generally upwind of the well pad and a residence 774 m (2,539 ft) and generally downwind from the well pad. Authors monitored for total VOCs continuously and collected intermittent 24-hour integrated air samples for 62 individual VOCs. Monitoring occurred after the well was drilled, and during four activity periods, including an inactive period prior to fracturing, during hydraulic fracturing, during flaring, and another inactive period following fracturing. Total VOC concentrations in ambient air during well activity periods were similar to inactive periods. Furthermore, individual maximum 24-hr VOC concentrations did not exceed subchronic or chronic US EPA Regional Screening Levels. However, this study monitored air quality during limited activities at the well pad (hydraulic fracturing, flaring) and did not capture other activities associated with oil and gas development (e.g., drilling, flowback, emissions from tanks and separators). This study also focused on a single well pad, and is likely not representative of air quality impacts of many well pads in a given region.

In another recent study, McKenzie et al. (2018a) used in-situ air pollution monitoring to estimate exposure and calculate risk across an array of distances plausible for residential proximity established based on setbacks from surface property lines in Colorado. Monitoring the concentrations of air pollutants (such as benzene) at various distances from active oil and gas development operations, the authors found compelling evidence that cancer and non-cancer risks and impacts increase as distance between oil and gas development and residential proximity decreases. Most notably, the study found that within 152 m (~500 ft) of active oil and gas development, the cancer risk estimate was 8.3 cases per 10,000 individuals, exceeding the US EPA upper threshold for acceptable risk (1 case in 10,000) by 830%. The majority of the studies on the topic of distance from and density of oil and gas wells and public health to date have used distance and density as the exposure metric but have been criticized for not including actual in-situ air quality measurements. This study is notably stronger than previous work given that it includes in-situ air quality measurements that show compelling evidence that concentrations of some hazardous air pollutants (HAPs) are higher near oil and gas wells compared to further away. These findings also raise questions about existing minimum surface setback requirements in Colorado, and the effectiveness of state and federal regulations to protect the health of those living near oil and gas facilities.

Elevated benzene concentrations observed by McKenzie et al. (2018a) are also bolstered by a recent study that found that the concentration of benzene in raw natural and associated gas in Wyoming has a median concentration of 88.5 ppm and up to 330 ppm (DiGiulio and Jackson, 2016). Given that the majority of gas is captured for market or flared and the relatively steep gradient that heavier hydrocarbons such as benzene fall out of the atmosphere moving away from their emission source, these are not the concentrations that nearby and downwind communities would likely be exposed to. However, these elevated source concentrations are important to consider when assessing hazard and risk of nearby populations. At this time there are limited publicly available data to adequately compare how benzene concentrations in California natural and associated gas resources compare to concentrations observed in Wyoming, given the dearth of publicly available data on benzene concentrations in gas produced from California oilfields. Nonetheless, intended and unintended venting, leaks, blowouts, subsurface stray gas migration and other emission events can result in benzene, a known human carcinogen, in the part per million (ppm) concentration to be emitted to the atmosphere. Emissions of certain pollutants, such as benzene at this concentration is certainly an occupational hazard (Esswein et al., 2014) and potentially a community hazard given that community health benchmarks of benzene exposure can be as low at 1 part per billion (ppb) (OEHHA, 2016).

Finally, McMullin et al. (2018) identified 56 VOCs emitted from oil and gas operations in Colorado and collated 47 existing air monitoring datasets in 34 locations in oil and gas regions. Authors aimed to characterize risk at and beyond 500 ft, and included air quality measurements that were collected between 350 and 3,700 ft from an oil and gas site. Authors found that acute and chronic non-cancer hazard quotients were not elevated for all individual VOCs, and hazard indices (HI) combining exposures for all VOCs were elevated for acute and chronic exposures (HI = 1.2 and 1.3, respectively). Similar to McKenzie et al. (2018a), the authors found lifetime excess cancer risk estimates for benzene were between 1 to 3.6 cases per 100,000 individuals and ethylbenzene was 7.3 cases per one million individuals. The lifetime excess cancer risk estimate for combined exposures was 4.3 cases per 100,000 individuals for distances between 500 ft and greater, exceeding the US EPA upper threshold for acceptable risk (1 case in 10,000). McMullin et al. (2018) lifetime excess cancer risk estimate also fell within the range reported by McKenzie et al. (2018a) for these same distances (1 case per 10,000 to 5.7 cases per 100,000).

4.6. Review of studies that investigate distance from and density of oil and gas development and associations with public health outcomes

While limited epidemiological data on oil and gas development and health has been collected in California, numerous epidemiological studies on this topic outside of California have been published. The health impacts evaluated by this body of literature include various health outcomes, including childhood and adult cancers, birth outcomes, upper and lower respiratory conditions, cardiovascular disease, fatigue, dermatological symptoms, migraines, sleep problems, and depression. In this section we discuss these 19 studies published between 2015 and 2018 in detail and present them organizationally by health outcome evaluated. Studies that use community-level exposure metrics (e.g. presence or absence of oil and gas development by zip code or county) are also discussed in this section. Most, but not all studies to date include distance from oil and gas development as at least part of the exposure metric considered. Studies that evaluate exposure using distance to oil and gas development are summarized in Table 4.

4.6.1. Cancer outcomes

A number of studies suggest that cancer risks increase with increasing proximity to oil and gas development (McKenzie et al., 2012; McKenzie et al., 2018a). Many studies posit, but do not confirm, that risks and incidence of hematological carcinogens, such as benzene, sourced from hydrocarbon reservoirs and co-emitted during oil and gas production are a likely mechanism (Garcia-Gonzales et al., 2019a).

McKenzie et al. (2017) investigated the potential association between residential proximity to and density of oil and gas development in rural Colorado and risk of hematologic (blood) cancers. Young individuals (ages 5-24) with acute lymphocytic leukemia (ALL) were over four times as likely to live in the highest well proximity and density category (<33.6 wells per 1.6 km, 5,249 ft) as compared to those not diagnosed with ALL [Odds ratio (OR): 4.3, 95% confidence interval (CI): 1.1-16.0]. A linear increase in risk of ALL was observed with increasing proximity and density exposure categories. No association was observed between proximity and well density for young children (ages 0-4) and for non-Hodgkin lymphoma. The authors cite exposure to benzene and other petroleum hydrocarbons in ambient air as well as elevated benzene concentrations detected in groundwater at oil and gas development sites in northeastern Colorado as potential environmental risk factors for childhood ALL. Furthermore, the researchers suspected that some limitations of this study may have biased the results toward the null, indicating that these findings may *underestimate* the true risk of hematologic cancer attributable to oil and gas development.

Another study in Pennsylvania showed the importance of considering legacy sources of pollution in an area experiencing oil and gas development. Finkel (2016) investigated unconventional natural gas development (UNGD) and cancer incidence in southwest Pennsylvania over time. Urinary bladder cases were higher than expected in counties with shale gas activity. Thyroid cancer cases increased over time, regardless of UNGD activity and patterns for leukemia incidence were mixed. Overall, observed cancer incidence was higher than expected prior to unconventional gas development in counties regardless of UNGD activity. While this study design is limited by county-level estimates of exposure, it makes the point that investigations into trends in cancer incidence associated with oil and gas development should take additional confounding factors, such a legacy pollution and the potential for synergistic toxic exposures into account.

4.6.2. Perinatal outcomes

A number of compounds associated with oil and gas development are associated with various perinatal outcomes (Balise et al., 2016; Webb et al., 2014). Four studies to date in Pennsylvania have focused on perinatal outcomes associated with natural gas development. Stacy et al. (2015) examined the association between proximity to UNGD in southwestern Pennsylvania and perinatal outcomes between 2007 and 2010. Inverse-distance weight well count within a mile – a measure of distance and density – was used to estimate exposure. While no association was observed for premature birth, comparison between the most exposed (≥6 wells per mile, 5,280 ft) to least exposed (<0.87 wells per mile, 5,280 ft) revealed lower birth weight (3323 ± 558 grams vs 3344 ± 544 grams) and a 34% higher incidence of small for gestational age (OR: 1.34; 95% CI: 1.10–1.63).

In another study focused on Marcellus shale gas development in Pennsylvania, Casey et al. (2016) used an Unconventional Natural Gas Development (UNGD) activity index as the exposure metric. This exposure metric includes variables such as distance to maternal residence, dates and duration of well activities (spudding, production, etc.), and well characteristics (depth and production) during gestation. UNGD activity was associated with a 40% increased odds of a neonate being born preterm (fourth quartile: OR: 1.4, 95% CI: 1.0 – 1.9) as well as a 30% increase odds of high-risk pregnancies among the mothers (fourth vs. first quartile, OR: 1.3, 95% CI: 1.1 – 1.7). The authors did not observe associations between UNGD and Apgar score (an index measurement of newborn physical condition), babies born small for gestational age, or term birth weight.

In another study, Currie et al. (2017) reviewed over 1.1 million birth records prior to and during extensive hydrocarbon development in Pennsylvania. Authors compared births up to 15 km (49,213 ft) from hydrocarbon development and also compared siblings born before and during development. An association was observed between maternal residential proximity to active unconventional oil and gas wells and increased incidence of low-birth weight babies and declines in average birth weight. The most significant impacts on birth outcomes were observed within 1 km (3,281 ft) of unconventional oil and gas wells, while little evidence of health effects was observed at and beyond 3 km (9,843 ft).

In a retrospective study focused on Marcellus shale gas development, Hill (2018) evaluated adverse birth outcomes among babies born to mothers living near shale gas wells between 2003 and 2010. Introduction of drilling was associated with increased low birth weight ($p<0.05$) and decreased term birth weight ($p<0.01$) on average among babies born to mothers living within 2.5 km (8,202 ft) of a well as compared to mothers living within 2.5 km of a permitted, but not yet drilled, well. Singleton births (a birth of a single baby) to mothers living within 2.5 km of a well were also associated with small for gestation age (SGA) ($p<0.05$) and reduced Apgar scores ($p<0.05$), while no effects were observed for gestation or congenital anomalies. In an evaluation of well density, an additional well drilled within 2.5 km of maternal residence was associated with a 7 percent increase in low birth weight, a 5 g reduction in term birth weight, and a 3 percent increase in premature birth.

Two studies examined birth outcomes and UNGD in the Barnett Shale region of Texas in recent years. Whitworth et al. (2017), using a retrospective birth cohort study design, studied 158,894 women with a birth or fetal death from November 2010 to November 2012. The researchers evaluated correlations between poor birth outcomes and well-activity metrics that included inverse distance-weighted sum of active wells within three separate geographic buffers surrounding the maternal residence: ½, two, or ten-miles (2,640; 10,560; or 52,800 ft respectively. Women with zero wells ≤10 miles near them served as the largest buffer evaluated and served as the control group. A significant association was observed between distance/density and preterm birth across all three distances: ½ mile (2,640 ft) (OR: 1.14, 95% CI: 1.03-1.25), two miles (10,560 ft) (OR: 1.14, 1.07-1.22), and ten miles (52,800 ft) (OR:1.15, 1.08-1.22) and for fetal death at two and ten miles (OR: 1.56, 95% CI: 1.16-2.11; 1.34, 1.04-1.72). No significant association was observed for small for gestational age or term birth weight. These results suggest that there is an association between unconventional gas development activity and preterm birth and fetal death. A shortcoming of this study, like many others in the literature is that the study did not collect in-situ air and environmental samples to evaluate the incidence and magnitude of potential chemical stressors that may be the mechanism behind these observed associations.

In a case-control study, Whitworth et al. (2018) – using the same birth dataset as Whitworth et al. (2017) - estimated the effect of UNGD on birth outcomes in the Barnett Shale region of Northern Texas. This study was notably more rigorous and detailed than Whitworth et al. (2017) as it included more nuanced exposure metrics and parsed exposures by gestational age. The researchers individually age- and race/ethnicity-matched five controls to each pre-term birth case (n = 13,328) and divided the fetal time at risk according to the matched case's gestational age. The study included two phase-specific UNGD-activity metrics: (1) a simple IDW count of wells in the drilling phase ≤ ½ mile (2,640 ft) of the residence and (2) an integrated IDW sum of natural gas produced ≤ ½ mile (2,640 ft) of the residence. The researchers also constructed trimester- and gestation-specific metrics. Metrics were categorized as follows: zero wells (reference), first, second, third tertiles of UNGD activity. Analyses were repeated by pre-term birth severity: extreme, very, and moderate (<28, 28 to <32, and 32 to <37 completed weeks). The study estimated an increased odds of preterm birth in the third tertile of the UNGD drilling {OR = 1.20 [95% confidence interval (CI): 1.06, 1.37]} and UNGD-production [OR = 1.15 (1.05, 1.26)] metrics. Among women in the third tertile of UNGD-production, associations were strongest in trimesters one [OR = 1:18 (1.02, 1.37)] and two [OR = 1:14 (0.99, 1.31). The greatest risk was observed for extremely preterm birth [third tertile ORs: UNGD drilling, 2.00 (1.23, 3.24); UNGD production, 1.53 (1.03–2.27)]. While the magnitude differences in preterm birth are small, the results of this study suggest that UNGD is associated with preterm birth and that associations are strongest when exposures occur in early pregnancy.

In a retrospective cohort study in Oklahoma, Janitz et al. (2019) evaluated congenital abnormalities among 476,000 singleton births and proximity to natural gas activity. Authors considered well density and distance within two miles (10,560 ft) of maternal residence during the month of delivery. Authors observed an increased prevalence of neural tube defects and specific critical congenital heart defects among neonates both to mothers living within two miles of natural gas activity compared to mothers living with no wells within two miles. However, these findings were not statistically significant. No association was observed for overall critical congenital heart defects or oral clefts (Janitz et al., 2019).

Biomonitoring, the collection of biological samples (e.g. blood, urine), can also be used to estimate individual exposure to contaminants. For pregnant women, biomonitoring can be used to characterize maternal exposure throughout fetal development. Caron-Beaudoin et al. (2018) detected developmental toxicants associated with oil and gas (e.g. benzene metabolites) in 29 pregnant women residing in unconventional gas producing areas of northeastern British Columbia (Canada). Benzene metabolites were detected at significantly higher concentrations in pregnant women living near gas development as compared to the general Canadian population (trans, trans-muconic acid concentrations, median = 180 ug/g creatinine; 10th percentile = 53.3; 95th percentile = 899). A significant shortcoming of this study is that although higher benzene metabolite concentrations were observed in the sampled population, source attribution is difficult given that this benzene metabolite is not specific to oil and gas development. A broader environmental assessment to rule out competing benzene exposures would be helpful to interpret the results in this study.

4.6.3. Cardiovascular and respiratory health outcomes and hospitalizations

Various peer-reviewed health studies have identified associations between oil and gas development and indicators of cardiovascular disease, respiratory outcomes (asthma and pneumonia), and hospitalizations for various health outcomes.

Only one peer-reviewed study has been published to date in California focusing on the Los Angeles region. Shamasunder et al. (2018) conducted household health surveys using questions from a validated health questionnaire (UCLA Center for Health Policy Research, 2016) within two 1,500 ft buffer areas surrounding the Jefferson and AllenCo oil production sites in the City Los Angeles. Physician-diagnosed asthma rates were elevated within both buffer zones compared to state-level and county-level surveys. Asthma prevalence was higher in one buffer zone (West Adams near the Jefferson drill site) than Los Angeles County. The study indicated that 45% of residents surveyed were reportedly unaware of nearby oil development. The study also included in situ air monitoring but only measured methane which may be a surrogate for non-methane VOC emissions from certain oil and gas infrastructure and processes, but there was no source apportionment and so the source of the methane is difficult to ascertain. To our knowledge, this is the most localized peer-reviewed assessment of asthma and oil and gas activities in the Los Angeles Basin. While this study compared localized asthma rates to state and county-level surveys, these comparisons do not take into account competing sources of air pollution – and other variables associated with asthma prevalence – and baseline demographic differences between these populations. It also relies on self-reported data, which can be difficult to interpret.

In a recent study in northeastern Colorado, McKenzie et al. (2018b) observed an association between the intensity of oil and gas activities and indications of cardiovascular disease. Using a cross-sectional study design (exposure and outcome evaluated at the same time), McKenzie et al. (2018b) recorded measurements of cardiovascular health and collected blood samples from approximately 100 adults in northeastern Colorado. The authors used an intensity adjusted inverse distance weighted exposure metric for wells within 16 km (52,493 ft) of each residence. This method allows for wells closest to each residence to contribute the most to that individual's exposure metric, unlike methods that use concentric buffers without adjustments for distance or intensity of activity. Greatest average plasma concentrations of systemic inflammation indicators were observed for those in the highest exposure group (>1,242 well intensity/km^2). Adjusted average augmentation index (a measure of arterial stiffness) differed by 6.0% (95% CI: 0.6-11.4%) and 5.1% (95% CI: -0.1 to 10.4%) between high and medium, respectively, and low exposure categories. For those not taking prescription medications, the adjusted average systolic blood pressure differed by 6 mmHg (95% CI: 0.1 to 13 mmHg) and 1 mmHg (95% CI: -6 to 8 mmHg) between the high and medium, respectively, and low exposure categories; no effect was observed for diastolic blood pressure. No association was observed with either systolic or diastolic blood pressure for those taking prescription medications. While these results suggest that there is an association between oil and gas activities and cardiovascular disease, this study was limited by its small sample size, its cross-sectional design, and its potential for confounding. Additionally, specific mechanisms of environmental stressors (e.g. air pollution or noise) were not evaluated. However, authors do note that inhalation of hydrocarbons has been associated with increases in cardiovascular emergency visits (Ye et al., 2017) and cardiovascular morbidity and mortality (Bard et al., 2014; Harrison, 2016; Villeneuve et al., 2013; Xu et al., 2009).

Numerous studies in Pennsylvania have investigated associations between patient hospitalizations and emergency room visits for respiratory and other health symptoms and UNGD in recent years. Jemielita et al. (2015) examined an association between unconventional gas wells and healthcare use by zip code from 2007 to 2011 across three northeastern counties. Cardiology inpatient prevalence rates were significantly positively associated with number of wells per zip code and wells per km^2 (3,281 ft^2), and neurology inpatient prevalence rates were significantly positively associated with wells per km^2 (3,281 ft^2). Evidence also supported an association between well density and inpatient prevalence rates for the medical categories of dermatology, neurology, oncology, and urology. These data may suggest that unconventional oil and gas development may be associated with increased inpatient prevalence rates within specific medical categories in Pennsylvania; however, these data may also indicate that unconventional oil and gas development disproportionately is sited in communities with higher existing disease burdens.

Willis et al. (2018) evaluated the association between UNGD and pediatric asthma hospitalizations in Pennsylvania between 2003 and 2014. The authors compared pediatric asthma hospitalizations among zip codes with and without UNGD activity, a community-level exposure metric including drilling activity and air pollutant emissions reported by site. Odds of pediatric hospitalizations were consistently elevated in the highest exposure category compared to those unexposed. A 25% increase in odds of pediatric hospitalization for asthma was observed if a well was drilled within the same quarter (OR: 1.25; 95% CI: 1.07, 1.47). Presence of UNGD within the same zip code over the entire study period was also associated with an increased odds of pediatric asthma hospitalization 1.19 (95% CI: 1.04, 1.36). These results suggest that UNGD sites and associated air pollutant emissions are associated with increased risks of pediatric asthma hospitalizations. A potential alternative hypothesis could be that places with UNGD have become less attractive to live in overtime and thus wealthier and healthier people have moved away leaving a higher proportion of less healthy asthmatics.

In another study in Pennsylvania, Rasmussen et al. (2016) investigated the association between UNGD development and asthma exacerbations in Pennsylvania. Authors conducted a nested case-control study comparing asthmatic patients with and without asthma exacerbations between 2005 and 2012. Exposure was assigned on the day prior to the exacerbation or control date using activity metrics based on well phase (i.e., well pad development, drilling, stimulation, production) and distance from patients' home to well, well characteristics, and dates and durations of phases. Associations were observed between the highest quartile of activity metric for each phase compared with the lowest for nearly all exposure-outcome pairs. Exposure-outcome associations ranged from pad development and severe asthma exacerbations (OR: 1.5, (95% CI: 1.2-1.7) to production and mild asthma exacerbations (4.4, 3.8-5.2) This study provides compelling evidence that residential UNGD activities are associated with mild to severe asthma exacerbations that may require emergency room visits and/or hospitalization.

Koehler et al. (2018) used three UNGD exposure metrics to evaluate potential associations with mild asthma exacerbations in Pennsylvania. The authors compared two previous approaches (1) distance to nearest well drilled (<1 km, 1-2 km, >2km; <3,281, 3,281 – 6,562, >6,562 ft) and (2) an inverse distance metric based on the drilling phase (wells within 16 km, 52,493 ft); and a novel inverse distance-squared metric incorporating four phases of development (well pad development, drilling, stimulation, production) and compressor engine activities. Each UNGD exposure metric (highest exposure category compared to lowest) was associated with mild asthma exacerbations. Using previous methods and exposure categories, this study shows how different exposure metrics may yield similar findings.

Peng et al. (2018) also investigated the health impacts of UNGD of Marcellus shale in Pennsylvania between 2001 and 2013 by merging well permit data from the Pennsylvania Department of Environmental Protection with a database of all inpatient hospital admissions. Authors found a significant association between shale gas development (counties with unconventional wells) and hospitalizations for pneumonia among the elderly, which is consistent with higher levels of air pollution resulting from UNGD. The study is limited in that it relied on county-level exposure characteristics rather than focusing on residential distance to oil and gas wells.

4.6.4. Additional health outcomes

Numerous studies in Pennsylvania investigate broad health symptom reporting and psychosocial outcomes. While these studies focus on proximity, density, and well activity, mechanisms and exposure pathways are not specifically evaluated.

Tustin et al. (2016) investigated associations between UNGD and symptoms in a cross-sectional study in Pennsylvania. Using a self-administered standardized and validated questionnaire, the authors identified respondents with chronic rhinosinusitis (CRS), migraine headache, and fatigue symptoms. The authors then used an UNGD activity metric that incorporated well phase, location, total depth, daily gas production and inverse distance–squared to patient residences. Of respondents reporting two or three of the health outcomes, significant associations were observed between highest UNGD activity category compared to lowest for CRS and fatigue (OR: 1.88; 95% CI: 1.08-3.25), migraine and fatigue (1.95, 1.18-3.21) and all three outcomes (1.84, 1.08-3.14). Results indicate that UNGD activity was associated with acute health symptoms, such as nasal and sinus, migraine headache, and fatigue, in the sampled population. However, the authors note that the surveyed population oversampled patients with nasal and sinus symptoms; therefore, survey respondents may be sicker than the general population, limiting the generalizability of these findings.

Weinberger et al. (2017) reviewed records structured health assessments conducted between February 2012 and October 2015 retrospectively for 51 adults who lived within 1 km (3,281 ft) of a well across three southwestern Pennsylvania counties. Reported symptoms were reviewed by a physician, and symptoms were excluded if they could be explained by pre-existing conditions or those than began or worsened prior to exposure, measured by date of well drilling within 1 km (3,281 ft). Symptoms most commonly reported were: sleep disruption, headache, throat irritation, stress or anxiety, cough, shortness of breath, sinus problems, fatigue, nausea, and wheezing. While health studies using self-reported symptoms can be limited, this assessment included a critical review of symptoms for possible alternative causes through physician review, and confirmation of timing of exposure to unconventional natural gas well relative to symptom onset or exacerbation.

Finally, Casey et al. (2018) evaluated the association between UNGD in Pennsylvania and depression symptoms and disordered sleep diagnoses using a validated health questionnaire and electronic health data. Exposure (very low, low, medium, high) was assigned retrospectively based on residential proximity to wells, UNGD activity, and well characteristics. Depressive symptoms were associated with increased well density and larger wells. Using two models, high exposure (as compared to very low) was associated with depressive symptoms (exponentiated coefficient = 1.18, 95% CI: 1.04–1.34), and high and low (compared to very low) were also associated with depression symptoms (High = 1.51, 95% CI 1.12–2.04; low = 1.63, 1.21–2.19). No association was observed for disordered sleep diagnoses. Authors note that the originally surveyed populations oversampled patients with nasal and sinus symptoms, and respondents may be sicker than the general population, limiting the generalizability of these findings. However, these findings suggest that UNGD may be associated with adverse mental health in a subset of Pennsylvanians.

4.6.5. Noise associated with oil and gas development

As discussed in the CCST SB 4 Report (2015), proximal populations experience disproportionate exposures to air pollution, noise, light associated with oil and gas development. While the assessment in this report has focused largely on air pollution, co-occurrence of multiple hazards from oil and gas activity readily occur and are important to consider. This section, separate from our systematic review, briefly summarizes the oil and gas development literature focused on proximity and noise.

Since the CCST SB 4 Report (2015), numerous additional studies have been published examining noise exposures (A- and C- weighted decibels, dBA and dBC) from oil and gas development and infrastructure near residential areas. A-weighted decibels (dBA) approximates the response of human hearing and is used for determining annoyance; C-weighted decibels are used to measure peak sound pressures when loud impulsive sources are expected (Wong, 2010).

Hays et al. (2017) reviewed the scientific literature on environmental noise exposure to determine the potential concerns, if any, that noise from oil and gas development activities present to public health. The authors found that data on noise levels associated with oil and gas development are limited, but measurements can be evaluated amidst the large body of epidemiology assessing the non-auditory effects of environmental noise exposure and established public health guidelines for community noise. The literature indicates that oil and gas activities produce noise at levels that may increase the risk of adverse health outcomes, including annoyance, sleep disturbance, and cardiovascular disease. More studies that investigate the relationships between noise exposure and human health risks from UOGD are warranted. Finally, policies and mitigation techniques that limit human exposure to noise from oil and gas operations should be considered to reduce health risks.

Radtke et al. (2017) monitored noise at oil and gas 23 sites in northern Colorado. At 350 ft, during three stages (drilling, hydraulic fracturing, and well completion) sites without noise barriers exceeded permissible noise levels for residential (55 dBA) and commercial (60 dBA) zones. Drilling and hydraulic fracturing sites with noise barriers also exceeded 55 dBA. At 107 m (350 ft) from the noise source, all drilling, hydraulic fracturing, and completion sites exceeded 65 dBC.

Boyle et al. (2017) evaluated noise from compressor stations used in oil and gas development and transmission that may pose risks to nearby communities in West Virginia. The authors found that noise levels exceeded both outdoor/daytime and indoor/nighttime US EPA decibel guidelines at homes less than 300 meters (985 ft) from a natural gas compressor station. Average indoor noise levels exceeded 40 A-weighted decibels (dBA), the level at which adverse health effects, such as sleep disturbance and insomnia, have been reported.

Another study, Blair et al. (2018), documented noise levels at a multi-well oil and gas well pad during construction and drilling in a residential area in Colorado over a 3-month period. Overall, 41.1% of daytime and 23.6% of nighttime dBA 1-min equivalent continuous noise measurements were found to exceed 50 dBA, and 97.5% of daytime and 98.3% of nighttime measurements were found to exceed 60 dBC. Measurements were taken within 320 - 550 m (1050 - 1805 ft) from the center of the well pad, exceeding the state regulatory setback distance (~152 m, 500 ft). Noise levels exceeding 50 dBA or 60 dBC may cause annoyance and be detrimental to health; thus, these noise levels have the potential to impact health and noise levels and associated health effects warrant further investigation. It would also be helpful for future studies like this one to help to characterize the extent to which their well pad and infrastructure samples are representative of these features more generally.

4.6.6. Summary of air pollution, noise, and health studies by distance

Studies are detailed by distance in Table 4. Increased risks from air pollution and elevated noise levels associated with adverse health outcomes have been observed in close proximity to oil and gas development. At 500 ft, the peer-reviewed literature suggests increased cancer risks (McKenzie et al., 2018a; McMullin et al. 2018) and elevated noise levels (Radke et al. 2017). Paulik et al. (2016) found no increased cancer risk at 500 ft, but the researchers only looked at PAHs rather than a wider array of pollutants identified in the literature. Elevated noise levels were also observed out to approximately 1,000 feet from compressor stations at levels at which adverse health effects, such as sleep disturbance and insomnia had been reported (Boyle et al. 2017). Furthermore, within 1,500-ft buffers around oil and gas sites in in Los Angeles, physician-diagnosed asthma rates were higher than state-level and county-level surveys. Asthma prevalence was also higher in a 1,500 ft buffer zone (West Adams near the Jefferson drill site) than Los Angeles County (Shamasunder et al. 2018). Additionally, a survey of experts determined that the minimum safe distance from unconventional oil and gas development is 1/4 mile (1,320 ft) and additional setbacks should be considered for vulnerable groups (Lewis et al. 2018; see Section 4.7).

Hazards, risks, and impacts attributable to oil and gas development are also observed in the peer-reviewed literature at 2,500 ft and beyond, including elevated noise levels (Blair et al. 2018), adverse birth outcomes (Currie et al. 2017; Hill et al. 2018; McKenzie et al. 2014; Stacy et al. 2015; Whitworth et al. 2017; Whitworth et al. 2018), increased non-cancer and cancer risks

(McKenzie et al. 2012), childhood cancer (McKenzie et al. 2017), and other acute adverse health outcomes (Weinberger et al. 2017). One peer-reviewed industry study (Maskrey et al. 2016) found that the maximum VOC concentrations did not exceed US EPA regional screening levels beyond 2,500 ft. However, numerous additional studies that have evaluated increased proximity, well density, and certain activities at the well pad have observed associations with adverse respiratory, cardiovascular, perinatal, mental health, and other acute health outcomes (Casey et al., 2016; Casey et al., 2018; Koehler et al., 2018; McKenzie et al., 2018b; Rasmussen et al., 2016; Tustin et al., 2016).

Table 4. Summary of health studies that estimate exposures to air pollution, noise, or other co-exposures as function of proximity to (or distance from) oil and gas development. Exposure metrics used may also incorporate well density, well pad activity. Studies are organized by distance evaluated and then alphabetically by lead author's last name.

Distance evaluated (ft)	**Publication**	**Region**	**Reported primary hydrocarbon produced**	**Source rock, migrated hydrocarbons or both?[1]**	**Study design**	**Study population and sample size**	**Findings**	**Health effect evaluated**
≤500	McKenzie et al. (2018a)	CO	Oil and gas	Likely both	Air monitoring; risk assessment	467 1-hr samples of benzene, toluene, and C9 aromatics (500 – 2,001 ft); 109 1-min non-methane hydrocarbons (NMHC) samples (≤500 - >5,249 ft); 59 72 or 96-hr NMHC samples (1,470 - >5,249 ft); 41 3-hr NMHC samples (810 ft).	Within 152 m (~500 ft) of active oil and gas development, the cancer risk estimate was 8.3 cases per 10,000 individuals, exceeding the US EPA upper threshold for acceptable risk (1 case in 10,000).	Non-cancer and cancer risk
	McMullin et al. (2018)	CO	Oil and gas	Likely both	Risk assessment	Air quality data for 56 VOCs, across 47 datasets and 34 locations collected 350 ft to 3,700 ft from an oil and gas site.	Acute and chronic non-cancer hazard quotients were not elevated for any individual VOCs; hazard indices (HI) combining exposure for all VOCs were elevated for acute (HI=1.2) and chronic (HI= 1.3) exposures. Lifetime excess cancer risk estimate for combined exposures was 4.3 cases per 100,000 individuals for 500 ft and beyond.	Non-cancer and cancer risk
	Paulik et al. (2016)	OH	Gas	Source rock	Air monitoring; risk assessment	23 passive air samplers monitoring for 62 polycyclic aromatic hydrocarbons (PAHs) over three to four weeks in 2014.	Within 0.1 km (~328 ft) of an active gas well, excess cancer risk estimate was 0.04 cases per 1,000,000, not exceeding the US EPA upper threshold for acceptable risk (1 case in 10,000).	Cancer risk
	Radtke et al. (2017) [2]	CO	Gas	Likely Both	Noise - direct sampling	Four dosimeters used per site (23); 92 noise samples collected at 350 ft	At 350 ft, during three stages (drilling, hydraulic fracturing, and well completion) sites without noise barriers exceeded permissible noise levels for residential (55 dbA) and commercial (60 dBA) zones. Drilling and hydraulic fracturing sites with noise barriers also exceeded 55 dBA. At 350 ft from the noise source, all drilling, hydraulic fracturing, and completion sites exceeded 65 dBC.	Noise

Distance evaluated (ft)	**Publication**	**Region**	**Reported primary hydrocarbon produced**	**Source rock, migrated hydrocarbons or both?[1]**	**Study design**	**Study population and sample size**	**Findings**	**Health effect evaluated**
≤1,000	Boyle et al. (2017)[2]	WV	Gas (compressor station)	N/A	Noise - direct sampling	Two (1 indoor and 1 outdoor) 24-hour measurements were collected at 8 homes (≤750 meters, 2,461 ft); 3 homes at >1,000 meters (3,281 ft) served as controls.	The authors found that noise levels exceeded both outdoor/daytime and indoor/nighttime US EPA decibel guidelines at homes less than 300 m (985 ft) from a natural gas compressor station. Average indoor noise levels exceeded 40 A-weighted decibels (dBA), the level at which adverse health effects, such as sleep disturbance and insomnia, have been reported.	Noise
≤1,500	Shamasunder et al. (2018)	CA	Oil	Migrated	Self-reported survey	Surveys were collected at 205 randomly sampled residences within two 1,500 ft buffer areas surrounding oil development sites in City of Los Angeles.	Physician-diagnosed asthma rates were higher within two 1,500 ft buffer zones, as compared to state-level and county-level surveys. Asthma prevalence was higher in one buffer zone (West Adams near the Jefferson drill site) than Los Angeles county.	Respiratory
	Lewis et al. (2018)[3]	n/a	Oil and gas	Unknown	Survey (Delphi)	18 panelists (health care providers, public health practitioners, environmental advocates, and researchers) were surveyed; consensus was defined as agreement of ≥70% of panelists.	A survey of experts determined that the minimum safe distance from unconventional oil and gas development is ¼ mile (1,320 ft) and additional setbacks should be used for vulnerable groups.	General (health)
≤2,500	Blair et al. (2018)[2]	CO	Oil and gas	Unknown	Noise - direct sampling	Four residences sampled (continuous 1-min) for 1 - 2 months depending on location.	Noise measurements detected between 320 m (1,050 ft) and 550 m (1,805 ft) from the center of the well pad, show exceedances in daytime and nighttime dBA and dBC measurements that are associated with annoyance, sleep disturbance, cardiovascular impacts, and other health effects.	Noise
	Paulik et al. (2018)[4]	OH	Gas	Source rock	Exposure assessment	30 passive samplers across 3 active and 2 proposed natural gas sites; 19 wristbands supplied to participants living or working near stationary sampling sites. Sampling included 62 PAHs.	Measured PAH concentrations were significantly higher in ambient air and from personal silicone wristbands in close proximity to active gas wells (2,461 ft), as compared to further away (6,562-32,808 ft).	Exposure

Distance evaluated (ft)	Publication	Region	Reported primary hydrocarbon produced	Source rock, migrated hydrocarbons or both?[1]	Study design	Study population and sample size	Findings	Health effect evaluated
>2,500	Currie et al. (2017)	PA	Oil and gas	Source rock	Retrospective cohort	1.1 million singleton births to women living in Pennsylvania from 2004 to 2013.	Low birthweight babies born to mothers within 1 km (3,281 ft) of unconventional oil and gas wells; little evidence of health effects observed at and beyond 3 km (~9,843 ft).	Perinatal
	Hill (2018)	PA	Gas	Source rock	Retrospective cohort	1,098,884 singleton births to women living in Pennsylvania, 2003 – 2010; Births within 2.5 km (8,202 ft) (n=21,610).	Increased low birth weight (LBW) and decreased term birth weight observed on average among babies born to mothers living within 2.5 km (8,202 ft). Proximity (<8,202 ft) was also associated with small for gestation age and reduced Apgar scores; no effects were observed for gestation or congenital anomalies. An additional well drilled within 2.5 km was associated with 7% increase in LBW, 5 gram reduction in term birth weight, and 3% increase in premature birth.	Perinatal
	Janitz et al. (2019)	OK	Gas	Unknown	Retrospective cohort	476,600 singleton births to women living in Oklahoma between 1997 and 2009.	Increased prevalence of neural tube defects and specific critical congenital heart defects was observed among neonates born to mothers living within two miles (10,560 ft) of natural gas activity. However, these findings were not statistically significant. No association was observed for overall critical congenital heart defects or oral clefts.	Perinatal
	Maskrey et al. (2016)	PA	Gas	Source rock	Air monitoring	Continuous total VOC monitoring, intermittent 24-hr integrated monitoring for 62 individual VOCs for three months, 2011 – 2012.	Total VOC concentrations in ambient air during well activity periods were similar to inactive periods. Individual maximum 24-hr VOC concentrations did not exceed subchronic or chronic US EPA Regional Screening Levels.	Cancer and non-cancer risk

Distance evaluated (ft)	Publication	Region	Reported primary hydrocarbon produced	Source rock, migrated hydrocarbons or both?[1]	Study design	Study population and sample size	Findings	Health effect evaluated
>2,500	McKenzie et al. (2012)[5]	CO	Gas	Likely both	Air monitoring; risk assessment	163 samples collected over 3 years; 16 (24 or 27-hr) samples 130 - 500 ft from 4 well pad locations during well completion with 1 background sample collected 1,742 – 5,280 ft from each well pad; 8 24-hour integrated samples 350 - 500 ft from the well pad during well completion activities.	Living within ½ mile (2,640 ft) of active oil and gas wells was associated with an increased risk of acute and sub-chronic respiratory, neurological, and reproductive health effects and slightly elevated excess lifetime cancer risk.	Non-cancer and cancer risk
	McKenzie et al. (2014)[5]	CO	Gas	Likely both	Retrospective cohort	124,842 singleton births to women living in Colorado between 1996 and 2009.	Using inverse distance weighted natural gas well counts within a mile (5,280 ft) to estimate exposure, authors found congenital heart defects increased with exposure and neural tube defects were associated with highest of exposure category (126 – 1,400 wells per mile, 5,280 ft) as compared to no exposure (0 wells within 10 miles, 52,800 ft). Exposure was negatively associated with preterm birth and positively associated with fetal growth, although the magnitude of association was small. No association was observed for oral clefts.	Perinatal
	McKenzie et al. (2017)	CO	Oil and gas	Likely both	Case-control (registry-based)	87 acute lymphocytic leukemia (ALL) cases, 50 non-Hodgkin lymphoma (NHL) cases, and 528 controls.	Young individuals (ages 5-24) with ALL were over four times as likely to live in the highest well proximity and density category (>33.6 wells per 5,249 ft) as compared to those not diagnosed with ALL. A linear increase in risk of ALL was observed with increasing proximity and density exposure categories. No association was observed between proximity/density for young children (ages 0-4) and for NHL.	Cancer

Distance evaluated (ft)	Publication	Region	Reported primary hydrocarbon produced	Source rock, migrated hydrocarbons or both?[1]	Study design	Study population and sample size	Findings	Health effect evaluated
>2,500	Stacy et al. (2015)	PA	Gas	Source rock	Retrospective cohort	15,451 singleton births to women living in southwest Pennsylvania between 2007 and 2010.	No association observed for premature birth. Lower birth weight and higher incidence of small for gestational age (SGA) observed with increased density at one mile (<0.87 wells vs. >6 wells per mile, 5,280 ft)	Perinatal
	Weinberger et al. (2017)	PA	Gas	Unknown	Retrospective survey (physician-reviewed)	135 structured health assessment records conducted between February 2012 and October 2015.	Physician-reviewed symptoms reported within 1 km (3,281 ft) of active well drilling included sleep disruption, headache, throat irritation, stress or anxiety, cough, shortness of breath, sinus problems, fatigue, nausea, and wheezing.	General (health)
	Whitworth et al. (2017)	TX	Gas	Source rock	Retrospective cohort	158,894 singleton births or fetal deaths to women living in the Barnett shale area between 2010 and 2012.	Significant association was observed between distance/density of unconventional gas wells at 0.5 mile (2,640 ft) for preterm birth and fetal death at 2 miles (10,560 ft).	Perinatal
	Whitworth et al. (2018)	TX	Gas	Source rock	Case-control (registry-based)	163,827 singleton births to women living in the Barnett shale area between 2010 and 2012.	Preterm birth was associated with increased proximity, density, and productivity of wells in the drilling phase within $^1/_2$ mile (2,640 ft), with greatest association observed for women in the first trimester.	Perinatal
Combined exposure metric[6]	Casey et al. (2016)	PA	Gas	Source rock	Retrospective cohort	9,384 mothers linked to 10,946 neonates in the Geisinger health records from 2009-2013.	Unconventional natural gas development (UNGD) activity was associated with preterm birth and physician-recorded high-risk pregnancy; no associations were observed for Apgar score, small for gestational age or term birth weight.	Perinatal
	Casey et al. (2018)	PA	Gas	Source rock	Retrospective cohort	4,762 participants with no (62%), mild (23%), moderate (10%), and moderately severe or severe (5%) depression symptoms in 2014–2015 and 3,868 disordered sleep diagnoses between 2009–2015.	Increased well density and larger wells were associated with depressive symptoms, but not disordered sleep.	Sleep / Depression
	Koehler et al. (2018)	PA	Gas	Source rock	Case-control	13,196 cases and 18,693 controls using Geisinger health records.	Using multiple UNGD activity metrics, UNGD was consistently associated with mild asthma exacerbations.	Respiratory

Distance evaluated (ft)	Publication	Region	Reported primary hydrocarbon produced	Source rock, migrated hydrocarbons or both?[1]	Study design	Study population and sample size	Findings	Health effect evaluated
	McKenzie et al. (2018b)	CO	Oil and gas	Likely Both	Cross-sectional	Adults in northeastern Colorado (n=97).	UNGD activity was associated with indicators of cardiovascular disease (arterial stiffness, elevated blood pressure, systemic inflammation).	Cardio-vascular
	Rasmussen et al. (2016)	PA	Gas	Source rock	Nested case-control	Patients with asthma aged 5 to 90 years (n = 35,508) were identified in Geisinger health records.	UNGD activity (pad development, drilling, stimulation, production) were associated mild and severe asthma exacerbations.	General (health)
	Tustin et al. (2016)	PA	Gas	Source rock	Cross-sectional	7,785 adult patients of the Geisinger Clinic.	UNGD activity was associated with chronic rhinosinusitis, migraine, and fatigue.	General (health)

[1] Determined by type of petroleum reservoir explicitly mentioned in the study; if not mentioned explicitly, we note the types of reservoirs produced from at the regional or state scale where the study took place.

[2] Studies evaluating noise levels near oil and gas development published since 2015, but not included in the systematic review.

[3] Study (discussed in Section 4.7) includes setback distance recommendations by health care providers, public health practitioners, environmental advocates, and researchers; health effects are not assessed.

[4] Exposure assessed at different scales (ambient air, personal exposure) and at gradient of distance; health effects are not assessed.

[5] Studies published prior to 2015 and discussed in the CCST SB 4 Report that evaluate air pollution and health effects by proximity to oil and gas wells.

[6] Studies using exposure metrics including multiple parameters, such as distance, density, activity at well pad, and well productivity.

4.7. Setback distances from oil and gas development and review of setback policies in the United States

A national spatial assessment of population proximity to oil and gas development found that 17.6 million Americans, including 2.1 million Californians, live within 1 mile (5,280 ft) of an active oil and/or gas well (Czolowski et al., 2017). Setback distances from oil and gas development can help mitigate proximal population exposures to air pollutants and other stressors associated with oil and gas activities that may be responsible for the observed human health risks and impacts in the peer-reviewed literature. Setback distances are typically established at the state or local level.

A few publications have discussed setback distances from oil and gas development and their associated effectiveness in reducing public health risks. Haley et al. (2016) investigated setback distances from unconventional oil and gas development in the Marcellus, Barnett, and Niobrara shale plays. In the areas studied, setback distances ranged from 150 to 1,500 ft. Given historical events and published modeling and air pollution data, the authors concluded that these existing setback distances do not appear sufficient to protect public health and safety from explosions, radiant heat, and air pollution from oil and gas development activities. Although the authors state that current legal setback distances are not adequate, no specific recommendations for setback distances are provided.

Lewis et al. (2018) surveyed a group of experts (researchers, scientists at government and regulatory agencies, and leaders in public policy and environmental advocacy) regarding safe distances from unconventional oil and gas development. Consensus (defined as agreement among 70% of participants) was reached determining that the minimum safe distance from unconventional oil and gas development is ¼ mile (1,320 ft) and additional setbacks should be used for settings where vulnerable groups are found, including schools, daycare centers, and hospitals. There was a lack of consensus around setback distances between ¼ - 2 miles (1,320 – 10,560 ft), due to limited health and exposure studies.

Webb et al. (2017) reviewed neurodevelopmental and neurological effects associated with chemicals used in unconventional oil and gas operations and the potential effects on infants and children. Upon review of Haley et al. (2016), the initial survey results presented in Lewis et al., (2018), and findings of McKenzie et al. (2012), Webb et al. (2017) recommended a setback distance of 1.6 km (5,249 ft) or greater for dwellings such as schools, hospitals, and other spaces where infants and children may frequent.

4.7.1. Review of setback policies in the United States

Existing setback distances for new development of oil and gas in the United States are summarized in Table 5. While California has no established statewide setback for oil and gas development, local jurisdictions have established setbacks for residences and sites of sensitive receptors. Recently in California, the City of Arvin adopted an ordinance that establishes setback distances of 300 ft for new development and 600 ft for new drilling operations near sensitive sites, such as parks, hospitals, and schools (City of Arvin, 2018). In addition to localized setback distances, California Code of Regulation defines a critical well as within 300 ft of a residence or airport runway or within 100 ft of a dedicated public street, highway, or operating railway; any navigable body of water; any public recreational facility, or any other area of periodic high-density population; or any officially recognized wildlife preserve (State of California, 2011). The Division of Oil, Gas and Geothermal Resources (DOGGR) requires operators to disclose if a proposed well for drilling meets critical well (CA DOC, 2018), implying that wells in close proximity to populations may pose greater risk to public health and safety.

Table 5. Summary of minimum surface setback distances from oil and gas development in the United States. Updated from LACDPH (2018) [1].

State	**Jurisdiction**	**Year Adopted**	**Setback Distance (ft)**	**Setback Target**	**Source**
California	City of Arvin	2018	300	New Development	City of Arvin (2018)
			600	Sensitive sites, such as parks, hospitals, and schools	
	City of Carson	2015	750	Housing, schools, hospitals	LACDPH (2018)
	City of Los Angeles	2011	200	School, hospital, sanitarium, or assembly occupancy	City of Los Angeles (2011)
			50	Building (>400 ft^2 area, 36 ft tall)	
	Los Angeles County	2013	100	Building not necessary to the operation of a well	LA County Fire Department (2013)
			300	Place of assembly, institution, or school	
	Kern County	2015	210	Housing, schools, hospitals	LACDPH (2018)
	SCAQMD[1]	2015	1,500	Requires notification of nearby sensitive receptors (residences, schools, health care facilities)	SCAQMD Rule 1148.2 (2015)
Colorado	State	2013	500	Housing or commercial buildings	LACDPH (2018); Haley et al. (2016)
			1000	High occupancy buildings – schools, day care centers, hospitals, nursing homes, and correctional facilities)	Haley et al. (2016); (COGCC (2013)
			350	Outdoor recreational areas (playgrounds and sports fields)	Haley et al. 2016; COGCC (2013)
			150	Surface property line	Haley et al. (2016); COGCC (2013)
Maryland	State	2016	1,000	Housing, schools, faith institutions	LACDPH (2018)
			2,000	Private drinking water wells	

State	Jurisdiction	Year Adopted	Setback Distance (ft)	Setback Target	Source
New Mexico	Santa Fe County	2008	750	Housing, schools	LACDPH (2018)
			1,000	Groundwater and surface water resources	LACDPH (2018)
Oklahoma	Oklahoma City	2015	300	Housing, fresh water well	LACDPH (2018)
			600	Faith institutions	LACDPH (2018)
Pennsylvania	State	2012	500	Housing and commercial buildings	Haley et al. (2016)
Texas	City of Arlington	2011	200	Fresh water well	LACDPH (2018)
			600	Housing, schools, faith institutions, hospitals	
	City of Dallas	2013	1,500	Housing, schools, faith institutions	LACDPH (2018)
	City of Flower Mound	2011	1,500	Housing, schools, faith institutions, hospitals, existing water wells	LACDPH (2018)
	City of Fort Worth	2010	200	Fresh water well	LACDPH (2018)
			600	Housing, schools, faith institutions, hospitals	

[1] Setback table updated with information from the peer-reviewed literature and California county and city policies.

[2] Distance that requires notification of sensitive receptors, not a setback distance.

The California Air Resources Board (CARB) recommended that sensitive receptors should not be located less than 1,000 feet from a variety of industrial land uses and stationary sources of air pollutant emissions including distribution centers, rail yards and chrome platers (CARB 2005). The CARB also recommends that sensitive receptors should be located at least 50 to 300 feet away from gasoline dispensing facilities based on their size.

Of note, in Table 5, oil and gas operators in the SCAQMD are required – pursuant to SCAQMD Rule 1148.2 – to notify SCAQMD if an oil and gas well event (drilling, re-work, routine maintenance, hydraulic fracturing, etc.) occurs within 1,500 ft of a sensitive receptor such as a residence, school, hospital, or other health care facility (SCAQMD, 2015). A total of 597 (35%) oil and gas well events in the SCAQMD were located within 1,500 ft of sensitive receptors, of which 368 (62%) were within 600 ft of the receptor (Table 6, Shonkoff et al. 2019b). Within the City of Los Angeles, 106 out of 131 total events (81%) were located within 1,500 ft of a sensitive receptor and 81 out of 131 (62%) of the events were within 600 ft (Shonkoff et al. 2019b).

Table 6. Number of oil and gas well events with associated chemical use reported within 1,500 ft of a sensitive receptor in the SCAQMD.

Distance to Sensitive Receptor (ft)	All SCAQMD Events	City of LA Events
0-300	115	47
301-600	253	34
601-900	132	5
901-1,200	49	13
1,201-1,500	48	7
Total	**597**	**106**

Data Source: SCAQMD (2019)
Table Cited From: Shonkoff et al. (2019b)

5.0. Relevance of results in the peer-reviewed literature to oil and gas development and public health in the City of Los Angeles

As noted, the most rigorous and thorough way to evaluate the presence and magnitude of health risks and impacts associated with oil and gas development in California would be to conduct studies on oil and gas and public health in the within the State of California. Unfortunately, as noted, there is only one health study to date on oil and gas development and public health outcomes in California (Shamasunder et al., 2018) and it relies only on self-reported health outcomes data – a type of data that is very difficult to interpret.

Health studies published since July 2015 have assessed health hazards, risks and impacts including but not limited to childhood and adult cancers, upper and lower respiratory conditions, cardiovascular outcomes, birth outcomes, hypertension, fatigue, dermatological symptoms, and migraines. While there continues to be a dearth of epidemiological and other health investigations on oil and gas development conducted in California, an increasing number of studies have focused on these issues in other parts of the United States and Canada. Some of these studies to date focus on types of oil and gas development and regulatory regimes that are uncommon in California – such as shale gas development and coal bed methane production – however many of the studies published since July 2015 are relevant to the California context given similar types of regional petroleum geology (e.g., migrated oil) and methods of oil and gas development (e.g., enhanced oil recovery and hydraulic fracturing of migrated oil deposits).

As noted earlier, there are a number of variables to consider when trying to assess the applicability of a given study to the California context in general and the City of Los Angeles context in particular. Some of the main variables include the following:

(1) the type of petroleum reservoir (source rock vs. migrated hydrocarbons)
(2) the type of hydrocarbon under production (e.g., oil, gas, or oil and gas)
(3) the technological approach to hydrocarbon production (e.g., high volume hydraulic fracturing, water flooding, steam injection, etc.)
(4) The types and intensities of emissions of criteria and hazardous air pollutants
(5) the regulatory environment (e.g., qualitative rigor of emission control regulations)
(6) the density of oil and gas development
(7) the density and demographics of human populations near the oil and gas development under evaluation

In Table 4, a number of these variables are noted in order to help to illuminate the studies that are likely to be the most relevant to the California and City of Los Angeles contexts. The studies that take place in states and jurisdictions with similar attributes to the City of Los Angeles context are those that evaluate health hazards, risks and outcomes from *migrated* oil and gas development in states with relatively stringent air pollution emission control regulations. For instance, The State of Colorado produces oil and gas both from source rock as well as migrated oil and gas with the use of more shallow hydraulic fracturing and the application of enhanced oil recovery. Also, Colorado, like California, has a methane emissions control rule which – if properly enforced – may significantly reduce emissions of methane, non-methane VOCs and other air pollutants from certain types of infrastructure during upstream oil and gas development. Below we explore some of the similarities and differences between the oil and gas development context in the City of Los Angeles and studies from other parts of the country.

5.1. Petroleum Geology and Type of Oil and Gas Development

The majority of the studies that represent petroleum systems most similar to California were conducted in the State of Colorado which has, like California, a diversified petroleum geological system with significant migrated oil and gas development from shallower formations. Production of Colorado oil, especially that in higher permeability, shallower geological formations is often enabled with enhanced oil recovery (EOR) methods, much like in the City of Los Angeles. Waterflooding, a primary type of EOR, is deployed significantly in the Los Angeles Basin in general as well as in the City of Los Angeles. Furthermore, Colorado, like California has a methane emissions reduction rule which – if properly enforced – may significantly reduce emissions of VOCs and other air pollutants from certain infrastructure during upstream oil and gas development.

Studies that focus on air pollution and human health associated with the development of oil and gas from source rock – for instance shale wells in the Marcellus Shale region of Pennsylvania or the Bakken Shale region of North Dakota – may differ from studies that could be conducted in California or City of Los Angeles in a number of key ways. First, unlike many of the oilfields in

City of Los Angeles that have been in production for more than one hundred years, the development of shale gas in the Marcellus has only been at scale since the mid-2000s. The development of oil and gas in new areas often means that the gas-gathering and water movement infrastructure has not been built out to the degree that it is with mature oilfield operations, which can result in increased gas venting and the use of trucks for movement of water on and off site.

Of course, there are also similarities between oil and gas production in Pennsylvania and California. While in recent years unconventional oil and gas has dominated public conversation around well development, conventional well development in Pennsylvania is by no means obsolete. According to 2017 PADEP production records, 89.5% of all active Pennsylvania oil and gas wells are conventional (PADEP, 2018a; Hill et al., 2019). Over the years 2013 to 2017, 2,228 new conventional wells were spudded in Pennsylvania, making up 32% of all wells spudded during this time frame (PADEP, 2018b; Hill et al., 2019). Meanwhile, an increasing body of literature suggests that various hazards and risks are intrinsic to both types of hydrocarbon production (Jackson et al., 2014; Lauer et al., 2018; Stringfellow et al., 2017; Zammerilli et al., 2014). While most health studies in Pennsylvania are explicitly focused on shale gas development, few studies consider whether conventional oil production and associated infrastructure may be playing a role in their observations of air quality and health hazards, risks and impacts.

The lack of insight into the petroleum geology and hydrocarbon type under production is a frequent shortcoming of health studies on oil and gas development in the peer reviewed literature. For instance, as noted, Colorado has a very diverse petroleum geology with oil, natural gas, associated gas and condensate being produced from source rock as well as migrated accumulations in shallower geologies. In Colorado, there is are geographic and geological propensities for hydrocarbon type with oil being more prominently found in the Denver-Julesburg Basin – e.g., the region where the study by McKenzie et al. (2018a) was conducted – and natural gas being more prominent in the Piceance Basin – e.g., where the study by McKenzie et al. (2012) was conducted. Despite this shortcoming – or perhaps in light of it – it is notable that the majority of peer-reviewed studies on oil and gas development have found associated hazards, risks and/or impacts to human health (Hays & Shonkoff, 2016).

5.2. Differences in Air Pollution Monitoring

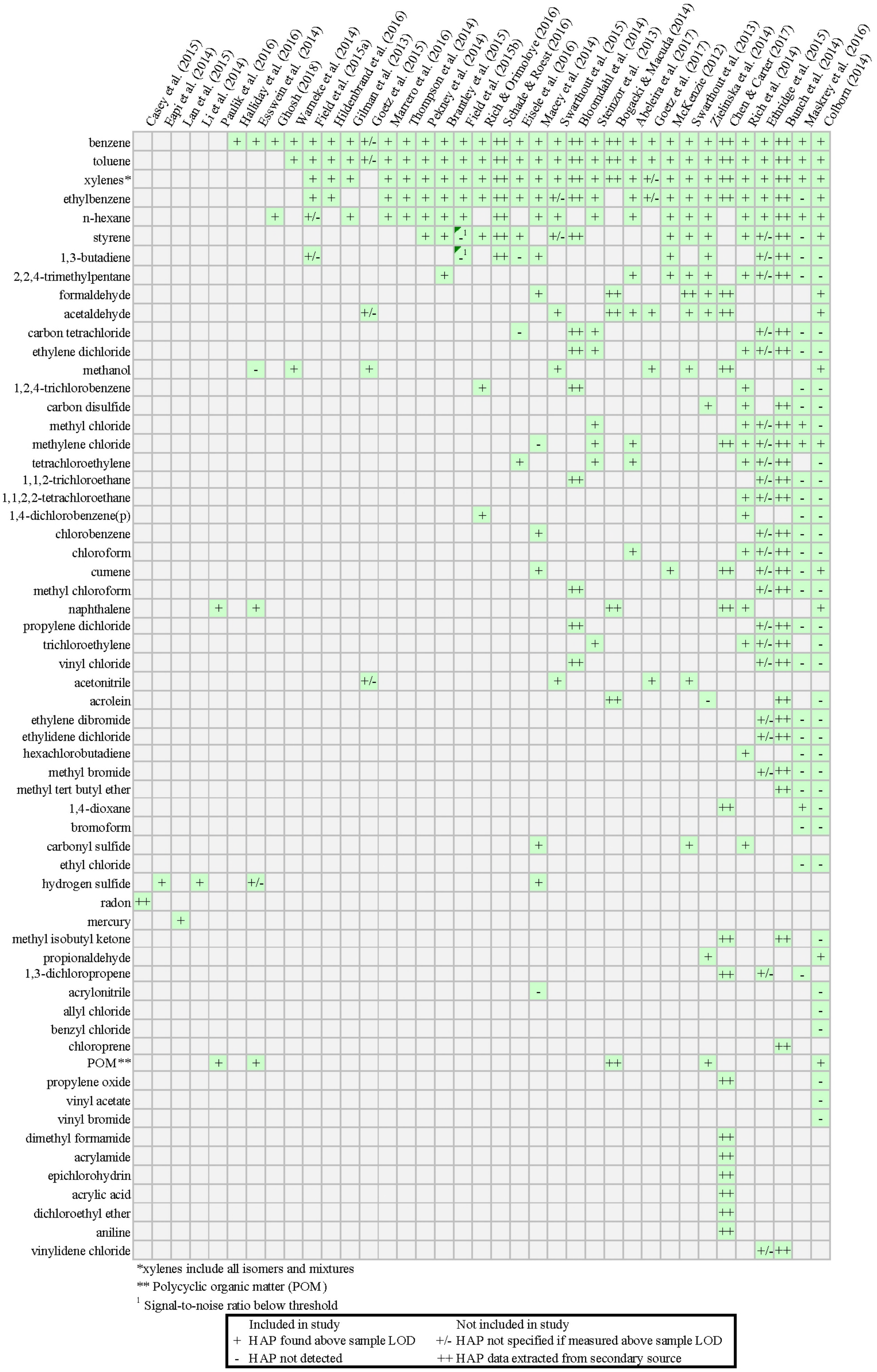
Given the use of exposure metrics (e.g., distance from and density of oil and gas development, volume of production of hydrocarbons, etc.) instead of in situ environmental measurements, it remains a challenge to determine which exposure or series of exposures may be driving the repeated observations of health impacts found in the peer-reviewed literature. While many of these studies posit that benzene and other air pollutants from oil and gas development activities may be driving these trends, the mechanisms of health impact remain uncertain. It is also possible that health impacts may be driven by pollutants that are not routinely monitored for, such as the volatile fraction of compounds used as additives in oil and gas development. The chapter in this report that assesses the SCAQMD 1148.2 database on chemicals used in oil and gas operations in the Los Angeles Basin, and City of Los Angeles in particular (Shonkoff et al. 2019b), evaluates what some of these compounds might be and what future air pollution monitoring efforts could expand their scope to focus on.

5.3. Overlap of types of pollutants emitted from the City of Los Angeles with those observed in the peer-reviewed literature

One way to compare the human health hazards of oil and gas development operations outside of the City of Los Angeles to those within the City of Los Angeles is to compare the types and intensities of emissions from the operations. As mentioned previously in this report, Garcia-Gonzales et al. (2019a) conducted a systematic review of peer-reviewed literature on hazardous air pollutants observed in emissions from and in the air near oil and gas development operations in the United States. The results of which HAPs were identified in the reviewed studies is shown below in Figure 3.

While there has been very limited in-situ air pollution monitoring around oil and gas development operations in the City of Los Angeles to date, the SCAQMD requires the reporting of toxic pollutant (many of which are HAPs) emissions from oil and gas operators in the State of California pursuant to The Air Toxics “Hot Spots” Information and Assessment Act (AB 2588, 1987, Connelly) enacted in 1987. The Hot Spots Program requires stationary sources to report the types and quantities of certain substances routinely released into the air. Many pollutants reported as emitted from oil and gas development pursuant to the Hot Spots Program to SCAQMD are also on the list of hazardous air pollutants observed at oil and gas operations nationally.

Figure 3. HAPs identified in studies from Garcia-Gonzales et al. (2019a).



	Casey et al. (2015)	Eapi et al. (2014)	Lan et al. (2015)	Li et al. (2014)	Paulik et al. (2016)	Halliday et al. (2016)	Esswein et al. (2014)	Ghosh (2018)	Warneke et al. (2014)	Field et al. (2015a)	Hildenbrand et al. (2016)	Gilman et al. (2013)	Goetz et al. (2015)	Marrero et al. (2016)	Thompson et al. (2014)	Pekney et al. (2014)	Brantley et al. (2015)	Field et al. (2015b)	Rich & Orimoloye (2016)	Schade & Roest (2016)	Eisele et al. (2016)	Macey et al. (2014)	Swarthout et al. (2015)	Bloomdahl et al. (2014)	Steinzor et al. (2013)	Bogacki & Macuda (2014)	Abeleira et al. (2017)	Goetz et al. (2017)	McKenzie (2012)	Swarthout et al. (2013)	Zielinska et al. (2014)	Chen & Carter (2017)	Rich et al. (2014)	Ethridge et al. (2015)	Bunch et al. (2014)	Maskrey et al. (2016)	Colborn (2014)
benzene						+	+	+	+	+	+	+	+/-	+	+	+	+	+	+	++	+	+	+	++	+	++	+	+	+	+	+	++	+	+	++	+	+
toluene									+	+	+	+	+/-	+	+	+	+	+	+	++	+	+	+	++	+	++	+	+	+	+	+	++	+	+	++	+	+
xylenes*										+	+	+		+	+	+	+	+	+	++	+	+	+	++	+	++	+	+/-	+	+	+	++	+	+	++	+	+
ethylbenzene										+	+			+	+	+	+	+	+	++	+	+	+/-	++	+		+	+/-	+	+	+	++	+	+	++	-	+
n-hexane								+		+/-		+		+	+	+	+	+		++		+	+		+		+		+	+	+		+	+	++	+	+
styrene																+	+	-[1]	+	++	+		+/-	++					+	+	+		+	+/-	++	-	+
1,3-butadiene										+/-								-[1]		++	-	+							+		+			+/-	++	-	-
2,2,4-trimethylpentane																	+										+		+	+	+		+	+/-	++	-	-
formaldehyde																						+				++				++	+	++					+
acetaldehyde													+/-										+			++	+	+		+	+	++					+
carbon tetrachloride																					-			++	+									+/-	++	-	-
ethylene dichloride																								++	+								+	+/-	++	-	-
methanol							-		+				+										+					+		+		++					+
1,2,4-trichlorobenzene																			+					++									+			-	-
carbon disulfide																															+		+		++	-	-
methyl chloride																									+								+	+/-	++	+	-
methylene chloride																						-			+		+					++	+	+/-	++	+	+
tetrachloroethylene																					+				+		+						+	+/-	++		-
1,1,2-trichloroethane																								++										+/-	++	-	-
1,1,2,2-tetrachloroethane																																	+	+/-	++	-	-
1,4-dichlorobenzene(p)																			+														+			-	-
chlorobenzene																						+												+/-	++	-	-
chloroform																											+						+	+/-	++	-	-
cumene																						+							+			++		+/-	++	-	+
methyl chloroform																								++										+/-	++	-	-
naphthalene					+		+																			++						++	+				+
propylene dichloride																								++										+/-	++	-	-
trichloroethylene																									+								+	+/-	++		-
vinyl chloride																								++										+/-	++	-	-
acetonitrile													+/-										+					+		+							
acrolein																										++					-				++		-
ethylene dibromide																																		+/-	++	-	-
ethylidene dichloride																																		+/-	++	-	-
hexachlorobutadiene																																	+			-	-
methyl bromide																																		+/-	++	-	-
methyl tert butyl ether																																			++	-	-
1,4-dioxane																																++				+	-
bromoform																																				-	-
carbonyl sulfide																						+								+			+				
ethyl chloride																																				-	-
hydrogen sulfide		+		+			+/-															+															
radon	++																																				
mercury			+																																		
methyl isobutyl ketone																																++			++		-
propionaldehyde																															+						+
1,3-dichloropropene																																++		+/-		-	
acrylonitrile																						-															-
allyl chloride																																					-
benzyl chloride																																					-
chloroprene																																			++		
POM**					+		+																			++					+						+
propylene oxide																																++					-
vinyl acetate																																					-
vinyl bromide																																					-
dimethyl formamide																																++					
acrylamide																																++					
epichlorohydrin																																++					
acrylic acid																																++					
dichloroethyl ether																																++					
aniline																																++					
vinylidene chloride																																		+/-	++		

*xylenes include all isomers and mixtures

** Polycyclic organic matter (POM)

[1] Signal-to-noise ratio below threshold

Included in study	Not included in study
+ HAP found above sample LOD	+/- HAP not specified if measured above sample LOD
- HAP not detected	++ HAP data extracted from secondary source

[1] LOD: limit of detection

Source: Garcia-Gonzales et al. (2019a)

It is difficult to directly compare the mass and intensity of emissions of pollutants between operations in the City of Los Angeles and other operations in the United States for a number of reasons, including:

- Emission reporting requirements, if they exist are not uniform across states and regional jurisdictions.
- Emissions reporting to the SCAQMD are not the result of field-based measurements, but rather estimates based on assumptions regarding emission factors from equipment and the number of units of that equipment deployed.
- Emissions reporting to SCAQMD is not temporally explicit. For instance, reporting refers to pounds per year, but does not provide information on the intensity of emissions at any given time during the year.
- Emissions are reported to SCAQMD at the facility scale and geographically explicit information is not provided.

An in-depth comparison of pollutants observed in the peer-reviewed literature with chemicals reported to SCAQMD is beyond the scope of this report. However, available information on emissions of toxic pollutants and hazardous air pollutants suggest that the types of pollutants emitted from oil and gas development operations in the City of Los Angeles are similar to those emitted from operations in other parts of the United States where health hazards, risks and impacts have been observed in studies.

5.4. Density of Oil and Gas Development

While distance from oil and gas development is – across many of the peer-reviewed studies – associated with increased health risks and endpoints, the density of oil and gas development is also noted as a key factor. For instance, in Colorado, McKenzie et al. (2014) found that incidence of congenital heart defects and neural tube defects were associated with the highest exposure category (126 to 1,400 wells per square mile) as compared to the lowest exposure category (0 wells within 10 square miles). Similarly, in a case-control study, McKenzie et al. (2017) found that young individuals (ages 5-24) with acute lymphocytic lymphoma (ALL) were over four times as likely to live in the highest well proximity and density category (>33.6 wells per square mile) as compared to those not diagnosed with ALL. Additionally, a linear increase in risk of ALL was observed with increasing proximity and density exposure categories. In order to assess similarities in the oil and gas development context between the City of Los Angeles and studies that have assessed density of oil and gas wells as a proxy for exposure, we conducted a spatial analysis on density of oil and gas wells in The City of Los Angeles.

5.4.1. Approach to well and population density assessment in and around the City of Los Angeles

In the context of the City of Los Angeles, it is important to identify the particular neighborhoods and communities that host the most extensive oil and gas development to be able to appropriately put the density of oil and gas development in the City of Los Angeles in the context of findings of health outcome associations with oil and gas well density in the body of peer-reviewed literature. To assess oil and gas development density in a comparable fashion to what exists in the peer-reviewed literature, we used measures of the spatial density of oil and gas wells as a proxy for oil and gas activity. To do this we conducted a census tract cluster analysis to determine the well density in the most oil and gas well-dense regions of the City of Los Angeles and adjacent areas.

To conduct this analysis we used the 2012 census tract boundary file with 2017 tract-level demographics provided by ESRI, Inc (ESRI, 2019) dataset which provides current estimates based upon the most recent American Community Survey (ACS) 5-year data (2009-2017) (US Census Bureau, 2019). We then buffered these tracts at 1,000 feet, as per guidance of the California Air Resources Board for recommended separation of sensitive land uses from significant sources of air toxics and other health-threat air pollution (CARB, 2017) and calculated a "preliminary well density" metric for each tract that reflects the number of oil and gas wells within the tract buffer.[3] This analysis was conducted for the entire area of the City of Los Angeles, but includes wells near the city boundaries, as these add to the total impact of well density on a given census tract and its residents. The frequency distribution of this metric, countywide, was evaluated using the Jenk's Optimization procedure to identify a natural break at 10 wells per square kilometer. Because of the highly clustered nature of oil and gas wells in Los Angeles, tracts with values higher than this are adjacent, creating "clusters" of census tracts which define areas of the highest oil and gas well density in this region. These tract clusters, were for the most prominent Los Angeles neighborhood within their area, and a final well density metric was calculated to reflect the number of wells per square kilometer for the tract cluster. A variety of human population metrics are reported, below, reflecting aggregated values for each tract cluster.

5.4.2. Results of well and population density assessment in and around the City of Los Angeles

The tract clusters that represent neighborhoods with the highest well density in the City of Los Angeles and adjacent areas can be seen in Figure 4.

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[3] Well data from DOGGR downloaded in March 2019; this analysis considers all wells described as either "active", "inactive" or "new"

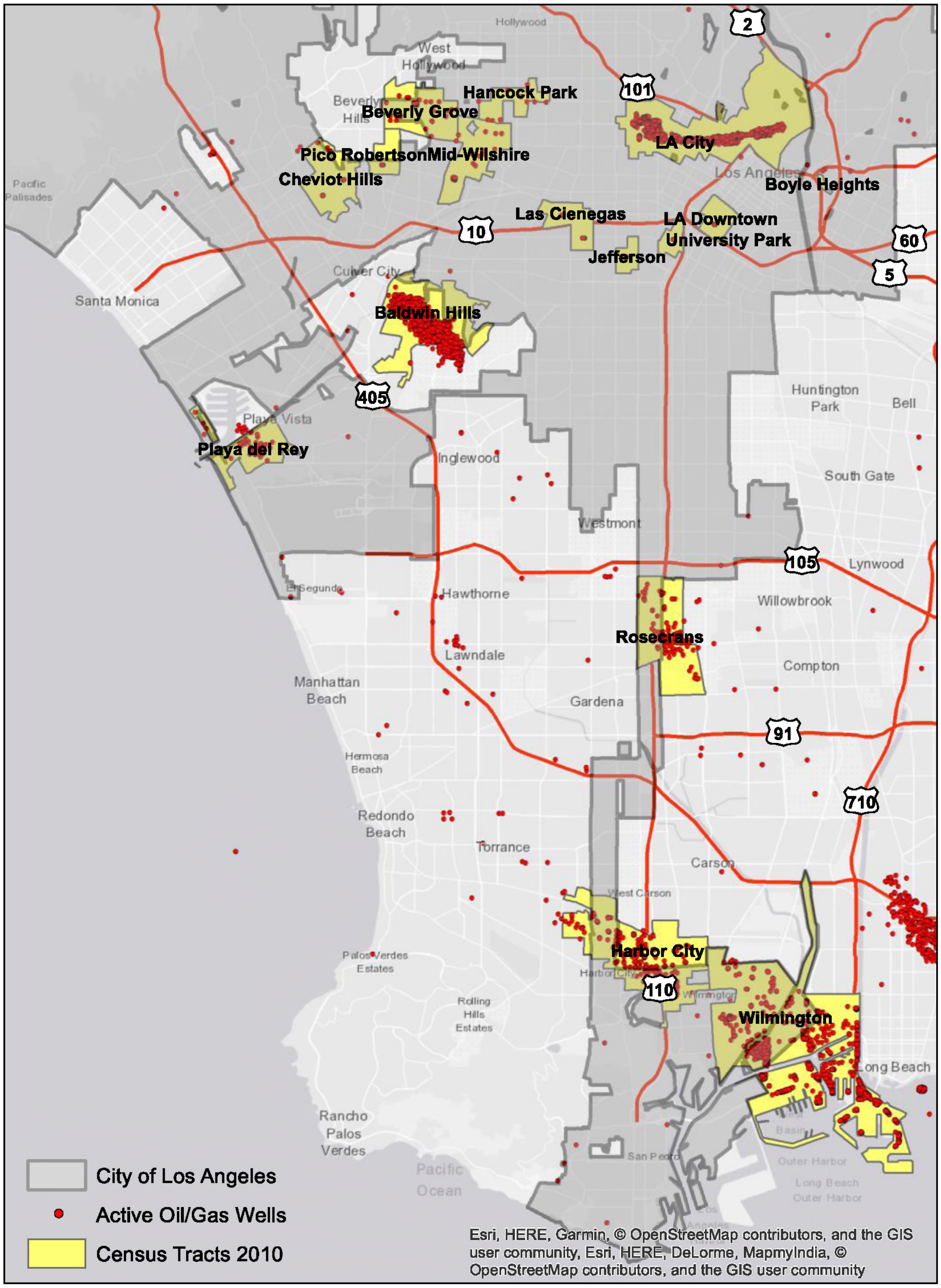


Figure 4. Clusters of census tracts (in yellow) named by neighborhood with the highest well density in the City of Los Angeles and adjacent areas. The dark-shaded portion marks the City of Los Angeles.
Source: Dr. James Sadd, Occidental College

In Table 7, we show the results of our analysis of oil and gas well and sensitive receptor density in neighborhoods within and near the City of Los Angeles. The highest well density in/near the City of Los Angeles is in the Baldwin Hills neighborhood which has 216 wells per square mile (83 wells per square kilometer). It should be noted that all of the wells near this neighborhood are located in unincorporated Los Angeles County. The highest well density within the City of Los Angeles is in the LA City Neighborhood (Koreatown, Westlake and Chinatown) with 162 wells per square mile (63 wells per square kilometer). Studies in the peer reviewed literature have found associations with poor birth outcomes, some childhood and adult cancers and other health outcomes at densities of 33.6 to 1,400 wells per square mile (13 to 540 wells per square kilometer). Using this range, 14 of the 15 tract cluster neighborhoods in the City of Los Angeles have oil and gas development (using oil and gas wells as a proxy) at the density associated with poor health outcomes in studies conducted in other parts of the country. In fact, density of oil and gas wells is in some cases higher per square mile in parts of the City of Los Angeles than the highest density category evaluated in studies in Colorado, Pennsylvania and Texas (Table 4).

Also of note in Table 7 is that the population density and demographics in the neighborhoods with high oil and gas well density. Population density is approximately 8,940 people per square mile (3,430 per square kilometer) throughout the City of Los Angeles and surrounding areas. The three highest population densities in high well density areas are found in the Jefferson (22,257 per square mile), University Park (22,237 per square mile) and LA City (Koreatown, Westlake, and Chinatown) (21,803 per square mile) neighborhoods. These population densities are much higher than those in rural Colorado, Pennsylvania and Texas where the majority of the peer-reviewed health studies have been undertaken. As such, while uncertainty exists as to how the emission profiles of oil and gas development in the City of Los Angeles compares to those in the studied areas in Colorado, Pennsylvania and Texas, what is clear is that emissions that do occur in the City of Los Angeles have a much higher intake fraction, i.e. the fraction of emissions that are inhaled by a human (Apte 2012; Marshall et al. 2003).

Table 7. Analysis of census tract clusters with the highest oil and gas well density within and near the City of Los Angeles, CA (Listed in order of well density).

Cluster	Tracts count	Wells count	Cluster total area (km2)	Cluster total area (mi2)	Well Density (km2)	Well Density (mi2)	Total population	Minority population	Total Housing Units	Owner-occupied housing units	Renter-occupied housing units	Med HH income
Baldwin Hills*	5	699	8.40	3.2	83	216	5,937	4,662	2,829	2,002	706	$90,139
LA City (Koreatown, Westlake, and Chinatown)	63	867	13.86	5.4	63	162	116,664	109,912	46,226	2,346	40,277	$33,644
Wilmington	16	1,582	25.99	10.0	61	158	17,242	16,605	4,741	1,755	2,742	$37,307
Jefferson	5	36	0.86	0.3	42	109	7,352	7,055	2,291	352	1,727	$34,521
Pico Robertson	7	58	1.40	0.5	41	107	7,988	1,832	3,635	1,042	2,302	$80,993
University Park	4	21	0.84	0.3	25	65	7,221	5,205	1,984	101	1,723	$16,975
Harbor City	20	236	11.16	4.3	21	55	41,266	34,616	13,069	7,904	4,736	$68,958
Mid-Wilshire	23	82	4.06	1.6	20	52	29,899	17,181	16,516	2,172	13,383	$74,105
Downtown LA	3	28	1.39	0.5	20	52	7,199	5,694	4,148	844	2,920	$41,127
Las Cienegas	10	43	2.17	0.8	20	51	14,701	13,999	5,043	992	3,620	$36,755
Beverly Grove	19	85	4.40	1.7	19	50	21,207	5,145	12,577	3,262	8,228	$85,552
Cheviot Hills	7	57	3.92	1.5	15	38	8,808	1,965	5,181	2,646	2,007	$119,945
Playa del Rey	6	52	3.70	1.4	14	36	7,282	2,080	3,943	1,794	1,889	$127,540
Harbor Gateway	10	93	7.11	2.7	13	34	13,084	12,810	3,908	1,835	1,836	$39,620
Hancock Park	6	7	1.90	0.7	4	10	6,214	989	2,607	1,238	1,237	$115,203
TOTAL	**204**	**3,946**	**91**	**35.2**	**-**	**-**	**312,064**	**239,750**	**128,698**	**30,285**	**89,333**	**-**

*Please note that wells in proximity to Baldwin Hills are located in unincorporated Los Angeles County.

Source: Dr. James Sadd, Occidental College

6.0. Discussion and research and policy recommendations

We reviewed the peer-reviewed literature to assess the weight of the evidence surrounding whether oil and gas development is associated with human health hazards, risks and impacts. Our broad conclusion is that the literature published to date strongly suggests that there are health hazards, risks, and potential impacts to communities that live, work and play in close proximity to and among high density of oil and gas development. While the magnitude of health risks and impacts associated with oil and gas development in the City of Los Angeles is not extensively characterized there are enough similarities between the types of operations studied outside of California to operations located in the Los Angeles Basin that this body of literature should be carefully considered by regulators and policy decisionmakers. Moreover, the population density near oil and gas development in the City of Los Angeles is much higher than in most of the places where oil and gas has been studied and, as such, should also be a carefully considered in policy decisionmaking.

While not all of the peer-reviewed studies published to date are directly applicable to the City of Los Angeles, the body of science that is most relevant – predominantly from the State of Colorado – strongly suggests that public health risks and impacts increase as a function of density of and distance from, oil and gas development. Further, the density of wells in the primary oil and gas development areas of the City of Los Angeles is similar to those densities of wells that have been associated with poor health outcomes in multiple studies across multiple states in the peer-reviewed literature. While oil and gas well density does not answer questions about relative emission rates and intensities and other factors that may influence exposure, it is clear that multiple factors are similar between studied oil and gas areas and the City of Los Angeles context. Further, as noted, population density in the City of Los Angeles and surrounding areas is significantly higher than the majority of places studied in the peer-reviewed literature. While this fact should not influence the oil and gas development operations, it does suggest that any emissions that do occur in the City of Los Angeles could impact a far greater number of people.

The State of California and the SCAQMD in particular has taken important regulatory steps to control emissions from upstream oil and gas development. The CARB has been working to implement landmark methane control legislation that may also control some additional sources of non-methane VOC emissions and air districts have promulgated regulations to reduce VOC and NOx emissions from a variety of emission sources within upstream oil and gas development. However, simultaneously there are some key uncertainties and potential shortcomings of these state and regional regulations. For instance, approaches to methane control under the CARB methane rule may not control emissions from certain sources of non-methane volatile organic compounds (NMVOCs) and aromatic hydrocarbons such as those from oil flashing.

6.1. Emerging Field-Based Air Pollution Measurements Near Oil and Gas Development in the Los Angeles Basin

6.1.1. Mellqvist et al., 2017

While this report is a systematic review of the peer-reviewed literature, it is worth briefly discussing a recent report authored by the SCAQMD given its relevance to the City of Los Angeles. In an effort to characterize VOC emissions from stationary industrial sources (e.g., oil and gas wells, refineries, gas stations) in the South Coast Air Basin, SCAQMD supported FluxSense measurement projects using optical remote sensing methods (Mellqvist et al., 2017). The quantification effort included 5,000 active oil and gas wells across 17 sites in the Los Angeles Basin. Oil and gas wells were associated the following relative contributions of emissions sources assessed: 53% of alkane and benzene, toluene, ethylbenzene, and xylene (BTEX) emissions; 40% of BTEX emissions, and 46% of benzene emissions. Emission rates from oil and gas wells were estimated to be 6,510 kg/h of alkanes, 467 kg/hour of BTEX, and 75 kg/h of benzene emitted from oil and gas wells (138 kg/h of alkanes, 0.075 kg/h BTEX, and 0.012 kg/h benzene per well). The authors emphasize that given the substantial number of sources that are located close to residential neighborhoods, these results suggest that further investigation is needed to better quantify the impact of small sources to the overall BTEX emissions in the region (Mellqvist et al., 2017).

6.1.2. Garcia-Gonzales et al. (2019b)

In a recent effort to characterize pollutant decay by distance from oil and gas wells at the Jefferson drill site in the City of Los Angeles, Garcia-Gonzales et al. (2019b) monitored for air toxics (benzene and n-hexane) and an oil and gas tracer compounds (n-pentane) at 11 residential sites within 245 m (804 ft) of the closest wellhead. On the eastern transect, benzene and n-hexane were found to decay to background levels at approximately 130 m and 195 m (427 and 640 ft), respectively; n-pentane was detected at background level from 165 m (541 ft), but concentrations increased at the furthest sampling location. The opposite was observed at the western transect, where n-pentane concentrations decreased with distance and benzene and n-hexane concentrations increased with distance; authors note that the western transect was likely influenced by another upwind pollution source. Notably, n-hexane concentrations were elevated above background at approximately 200 m (656 ft) from the closest wellhead.

6.1.3. Study of Neighborhood Air Near Petroleum Sources (SNAPS)

Some remaining data gaps may be filled through the Study of Neighborhood Air near Petroleum Sources (SNAPS) program run by the CARB. The SNAPS program is tasked with measuring air pollutant concentrations near oil and gas operations at the community level throughout the State of California.

The SNAPS program – if air quality data is collected in ways that appropriately captures the episodic nature of diverse emissions from upstream oil and gas systems – may provide important information for researchers, regulators and communities on questions surrounding human health risks associated with California oil and gas development activities. However, SNAPS is a single study and prudence should be exercised in over-extrapolating the validity of its results – positive or negative – to oil and gas development in general across temporal, geographical, geological, oil and gas operator and regulatory space in California. SNAPS results should be critically examined, compared against and integrated with results of other studies in the field, including those reviewed in this report.

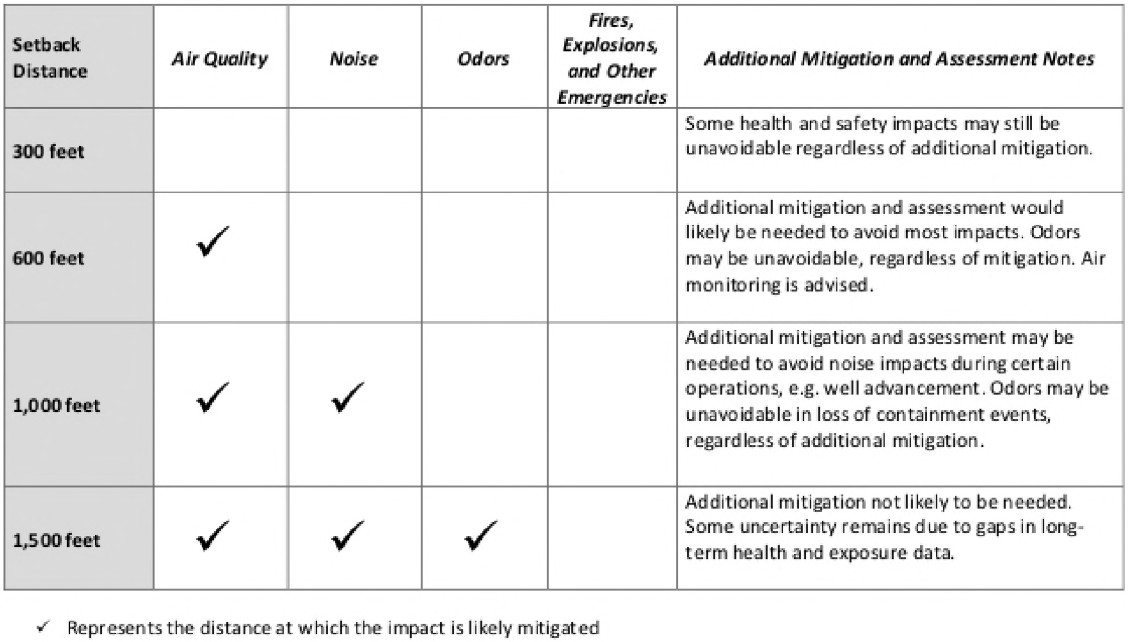
6.2. The consideration of minimum surface setbacks to protect public health

The science is relatively clear that the development of oil and gas immediately adjacent to places where people live, work and play poses hazards and risks to public health and that some minimum distance from sensitive receptors should be considered. Texas, Pennsylvania, Colorado, New Mexico and other major oil and gas producing states have regulations that set a minimum surface setback requirement from sensitive receptors where oil and gas can be produced and in most cases these setback requirements are larger than those that exist in the City of Los Angeles and the State of California more generally.

The determination of how far is far enough is complex, especially given that much of the literature to date has also identified the *density* of oil and gas development to be a key factor associated with health risks. Nonetheless, analysis in this report has concluded that 14 of the 15 most oil and gas well-dense areas in the City of Los Angeles are at or above well density that has been associated with health hazards, risks and impacts in peer-reviewed studies from other parts of the country (see section 5.4).

LACDPH (2018) in their recent report provide helpful guidance with respect to recommendations for a setback policy in the City of Los Angeles. A summary of their assessment with respect to mitigation of health risks as a function of distance can be found below in Table 8 below. It should be noted that LACDPH reviewed Los Angeles County health complaints data and environmental impact statements in their assessment, yet included a more limited number of peer-reviewed air pollution and epidemiological studies than we did in this report.

Table 8. Mitigation of human health and emergency risks as a function of distance.



Setback Distance	*Air Quality*	*Noise*	*Odors*	*Fires, Explosions, and Other Emergencies*	*Additional Mitigation and Assessment Notes*
300 feet					Some health and safety impacts may still be unavoidable regardless of additional mitigation.
600 feet	✓				Additional mitigation and assessment would likely be needed to avoid most impacts. Odors may be unavoidable, regardless of mitigation. Air monitoring is advised.
1,000 feet	✓	✓			Additional mitigation and assessment may be needed to avoid noise impacts during certain operations, e.g. well advancement. Odors may be unavoidable in loss of containment events, regardless of additional mitigation.
1,500 feet	✓	✓	✓		Additional mitigation not likely to be needed. Some uncertainty remains due to gaps in long-term health and exposure data.

✓ Represents the distance at which the impact is likely mitigated

Source: LACDPH (2018), p. 22

As noted in Table 8, LACDPH (2018) asserts that concentrations of health-damaging air pollutants are expected to fall considerably around 600 ft from their emission source, but additional mitigation measures (e.g., heightened emission controls) should also be deployed as well as air pollution monitoring to screen for effectiveness. The LACDPH also concludes that most key public health and safety hazards would likely be mitigated at 1,500 ft from the emission source, with the exception of risks posed by fires, explosions and other emergencies.

The conclusions of the LACDPH (2018) report agree to a large degree with the findings in this literature review. The heavier and conserved air pollutants, such as benzene have a steep air concentration gradient as they move away from their emission source. However, as noted earlier, most of the studies that assess health risks and impacts as a function of distance in the peer-reviewed literature do not consider distances less than 2,500 ft due to the need for population sample sizes large enough to power their study and the majority – but not all – of these studies have found evidence of health impacts associated with oil and gas development at this distance.

Additionally, as noted in Shonkoff et al. (2019b), SCAQMD Rule 1148.2 requires reporting distance of oil and gas well events from sensitive receptors. Of note, 62% of oil and gas well events reported to this database between 2013 and 2018 in the City of Los Angeles occur within 600 ft of sensitive receptors. This may be important given that 40 (12%) chemicals reported to the SCAQMD dataset were identified on air pollution screening lists, of which 24 were used in the City of Los Angeles. A total of 22 chemicals were identified as hazardous air pollutants (HAPs) under the Clean Air Act, half of which were reported as used in the City of Los Angeles (Shonkoff et al. 2019b).

Recent published reviews of the literature (Johnston et al., 2019; Stacy, 2017) call for improved characterization of exposures by community health studies as vital to determine the full range of health risks to populations near oil and gas extraction. Given that it takes time to develop, implement, and publish peer-reviewed epidemiological research, strategies to mitigate community exposures should be undertaken. These approaches may include the implementation of minimum surface setbacks, emissions control technologies, caps on the number of oil and gas wells that can be sited per unit area, and other strategies (CCST, 2015). These types of exposure reduction strategies may be particularly beneficial in areas of high population density near dense oil and gas development, such as in the City of Los Angeles.

Below we list the key findings, conclusions and recommendations (FCR) that emerged from our assessment of the peer-reviewed literature:

6.3. Findings, Conclusions and Recommendations

Below we summarize our main findings, conclusions and recommendations (FCR) from this review of the literature and assessment of applicability to the City of Los Angeles Context.

FCR-1: Conduct studies in the State of California to assess the relationship between oil and gas development and public health as a function of distance.

Finding: Only one peer-reviewed oil and gas development and health study has been conducted in the State of California. There are however a variety of results and conclusions drawn from the greater peer-reviewed literature outside of California that are applicable to the California context.

Conclusion: There is a dearth of peer-reviewed studies on oil and gas development that are specific to the State of California and the City of Los Angeles, yet there are results and conclusions drawn from the weight of the peer-reviewed literature outside of California that are relevant to the California context.

Recommendations:

(1) Conduct health studies in the City of Los Angeles on the health dimensions of oil and gas development as a function of distance and oil and gas well density that incorporate multiple potential environmental and exposure pathways. These studies should assess active oil and gas development and could also include inactive oil and gas development such as plugged and abandoned wells and associated infrastructure. Given the increasingly expansive body of health literature on the topic, consider promulgating health-protective policies based on the existing literature.

(2) Ensure that field-based air pollution monitoring at the community scale and in close proximity to oil and gas development continues and expands and that it is implemented in ways that properly characterize emissions from these processes. This includes but is not limited to ensuring that air monitoring methods are deployed to capture the intermittent and periodic nature of emission events throughout the oil and gas development process and

that there is access to well pad-level activity information to inform the monitoring approaches.

FCR-2: Consider the implementation of a minimum surface setback requirement, caps on oil and gas development density and deployment of increased emission control strategies in the City of Los Angeles.

Finding: The majority of peer-reviewed studies that assess human health in the context of oil and gas development as a function of distance and density have noted increased hazards, risks and health impacts as distance decreases and density increases. The density of oil and gas development in oil and gas-producing neighborhoods in and near the City of Los Angeles is as high or higher than densities of oil and gas development associated with health impacts in out of state studies.

Conclusion: The development of oil and gas close to human populations poses higher risks of exposure to health-damaging air pollutants than the development of oil and gas further away from human populations. The same trend tends to exist for higher vs. lower density of oil and gas development.

Recommendations:

(1) Agencies with jurisdiction should consider the implementation of minimum surface setbacks between oil and gas development and sensitive receptors including but not limited to residences, schools and hospitals in the City of Los Angeles. The distance determined should, at a minimum, be far enough that heavier conserved air pollutants such as benzene have time to fall out of the atmosphere before reaching sensitive receptors. The decision as to how large the setback is should also take the available body of epidemiological studies into account. Studies to date conducted in regions with migrated hydrocarbon reservoirs have found associations with increased health risks associated with oil and gas development ranging from approximately 0.1 miles (500 feet) to one mile (5,290 feet). As such, a setback greater than 500 feet and up to 5,290 feet should be considered.

(2) Given that the *density* of oil and gas development has been found across a number of health studies to be associated with increased health risks, agencies with jurisdiction may consider limiting the density of wells and other oil and gas development infrastructure at oil and gas producing areas within and near the City of Los Angeles.

(3) Best available emission control technologies and management approaches should be deployed on all oil and gas wells and ancillary infrastructure to limit emissions of health-damaging air pollutants. Target air pollutants should include both those that are regularly monitored for (e.g., Criteria Air Pollutants, TACs and aromatic hydrocarbons such as benzene) as well as those pollutants that are less frequently monitored for including, but not limited to chemicals reported to SCAQMD pursuant to Rule 1148.2 that are known air pollutants.

7.0. References

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