An analysis of the impact of unconventional oil and gas activities on public health: New evidence across Oklahoma counties

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ABSTRACT

The expansion of unconventional oil and gas development (UNGD) in the US has been highly controversial so far with no consensus on its health, economic, environmental, and social implications. This paper examines the effects of UNGD on the health profile of the population in the context of Oklahoma using a unique data set. To this end, the analysis assembles a panel data set including 76 counties of Oklahoma, spanning the period 1998-2017. The analysis estimates the long-run relationship between the health profile and its determinants using the Common Correlated Effects (CCE) method. The empirical setup allows for cross-sectional dependence and accounts for both observed and unobserved heterogeneity. The main findings provide strong evidence that UNGD activities have negative effects on human health-related outcomes across all counties in Oklahoma. Specifically, an increase in the number of (unconventional) wells has a positive impact on mortality rates, and incidences of cancer, cardiac, and respiratory diseases in communities in close spatial proximity, and a negative impact on life expectancy. These findings provide evidence that UNGD activities pose significant risks to the public health profile across the Oklahoma population. Such findings are expected to have substantial implications for the national debate on the regulation of UNGD.

Keywords: unconventional oil and gas activities; public health; Oklahoma counties

JEL Classification: Q43; I12; C33

1. Introduction

In the early 2000s, the US experienced the beginning of a resource boom after horizontal drilling and hydraulic fracturing technologies were combined in a way that made it economical to extract oil and gas from tight, or unconventional, geologic formations (McNally et al., 2018). The US holds large unconventional gas reserves (i.e., gas trapped in impermeable rock deep underground) in the form of coal beds, shale, and tight gas sands. The US and Canada together account for almost all commercial global shale gas production where the technological advancements, such as hydraulic fracturing (commonly known as fracking), have made it possible and economically feasible to explore shale gas from these former unreachable geological formations (Hill, 2018). In 2015, the crude oil production from fracking wells accounted for half of total U.S oil production (Energy Information Administration, 2016).

With the expansion of fracking at such a large scale, these activities are taking place in close proximity to where people live, work, or play. The Wall Street Journal estimates that nearly five million residents in the US live within one-mile proximity of an oil or gas well (Gold and McGinty, 2013). The expansion of fracking activities in the US has been extremely controversial so far with no consensus on its health, environmental and social implications (Hill, 2018)[1]. The 'boomtown' phenomenon may lead to economic benefits, where local areas experiencing fracking activities see increases in employment, housing prices, population, and consumer's and producer's

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[1] For instance, on one hand, there is a vast gamut of literature which demonstrates the harmful effects of fracking on health of the local population. On the other hand, there are studies which question these findings. A 2019 Health Effects Institute report reviews 25 epidemiology studies published between January 2000 and December 2018 that sought to establish a connection between various health outcomes and unconventional oil and gas developments. The report concludes that there is no systematic link between the two, arguing that the cancer studies show weak or no correlations and cites data limitations as a major shortcoming of most of the studies on respiratory, physiological and mental health issues. Bamber et al. (2019) review 20 epidemiologic studies with 32 different health outcomes and they conclude that there exists limited evidence on the harmful health effects (including asthma exacerbations and various self-reported symptoms), as far as oil and natural gas activities are concerned.

welfare (Apergis, 2019; Marchand and Weber, 2017; Hausman and Kellogg, 2015, Fetzer, 2014; Weber, 2012).

In addition to the economic benefits of shale gas development, the proliferation of fracking activities in the US has resulted in energy plants moving from coal to unconventional shale gas for producing electricity, thus, reducing emissions in the power sector. Further, natural gas is used as fuel in transportation and can be used in residential heating in addition to its industrial uses (U.S. Energy Information Administration, 2017). However, such benefits may come at a significant cost to the local population. The local communities in boomtowns may have to suffer from negative health, economic, environment and social consequences, such as premature birth, lower housing values due to seismic activity, poor air quality, and higher levels of alienation (Carpenter, 2016; Hill, 2018; Ng'ombe and Boyer, 2019).

Moreover, the ‘boom’ might be temporary only and followed by a ‘bust’ if advantages from fracking activities are only on a short-term basis.[2] Rickman and Wang (2020), in fact, demonstrate this in the context of Oklahoma. The authors investigate potential asymmetries in responses of total nonfarm employment across the cycle based on the initial boom period (2004–2008), a post-recession boom period (2010–2014), and a bust period in the oil and gas sector that diverge from overall national economic trends (2014–2016). The study documents differing employment impacts across Louisiana, North Dakota, Oklahoma, and Wyoming in both the short and long run, as well as asymmetries during the boom-bust phases. Furthermore, the findings illustrate that pro-cyclical fiscal responses of Oklahoma likely contribute to their larger negative employment multiplier effects during the bust period. Moreover, the analysis shows

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[2] Rickman et al. (2017) document that shale booms in Montana, North Dakota, and West Virginia cause significant reductions in high school and college attainments.

that despite approximately a 40% rise in oil and gas jobs in Oklahoma, total nonfarm wage and salary employment in the state decrease by over seven and one-half thousand because of the oil and gas cycle. The local areas might experience an expansion in public goods throughout the boom period at significant cost only to be later left underutilized. In addition, the boomtowns may suffer from the “Dutch Disease” phenomenon as sectors with better development prospects contract throughout the expansion period, leaving the local areas worse off in the long run (Muehlenbachs et al., 2015). Recent research provides evidence on the loss of other economic activity consistent with Dutch Disease and/or resource curse results (Rickman and Wang, 2020).

A growing body of literature has investigated the impacts of fracking on the health profile of the population. The communities surrounding the fracking activities may experience negative consequences on their health profile. For example, the population near shale gas wells may be affected via physical hazards, including noise, light, vibration, and ionizing radiation that can damage the health of individuals directly, as well as indirectly via stress pathways (Gorski and Schwartz, 2019). There is growing evidence that shale gas development poses significant risks to public health. A relatively recent study provides robust evidence that an additional shale gas well in Pennsylvania is associated with a 7 per cent increase in low birth weight, a 5-gram reduction in terms of birth weight, and a 3 per cent increase in premature birth (Hill, 2018). Furthermore, mothers living in proximity to hydraulic fracturing activities may experience high-risk pregnancies (Casey et al., 2016), while the health of local population may also suffer due to water contamination and air pollution (Bamberger and Oswald, 2012; Carpenter, 2016). Likewise, hydraulic fracturing is associated with nasal and sinus, migraine headache, and fatigue symptoms (Tustin et al., 2017). Finally, fracking is found to be a major cause of depression and sleep disorders in Pennsylvania, thus confirming that fracking has a serious negative impact on both the physical and mental wellbeing of people living in proximity to shale gas wells (Casey et al., 2018). As a result, there are serious concerns among the scientific community that the fracking industry is an uncontrolled health experiment on a colossal scale (Bamberger and Oswald, 2012).

Fracking is significantly higher in Oklahoma, Pennsylvania, Texas, Louisiana, and Arkansas as compared to eighteen other US states. Shale gas extraction has proved to be economical and efficient in the populated North Eastern US, and currently provide the main share of the U.S. gas supply. Yet, some strong opposition to fracking has emerged, citing the potential for serious negative impacts on the public health profile due to water contamination, methane leakage, and the local environment due to air pollution (Gorski and Schwartz, 2019; Mason et al., 2015).

Oklahoma State has experienced an upsurge in oil and gas (O&G) production since 2006. The state has a rich history and association with O&G production and extraction as these operations are deeply embedded in its political, social, and cultural environment (Raynes et al., 2016). Oklahoma's oil history began when oil was discovered in 1897 after a column of oil erupted from a well near Bartlesville[3]. The O&G industry hired approximately 130,225 workers in 2015 and paid a total of $2 billion as direct state taxes to Oklahoma tax authorities (State Chamber of Oklahoma Research Foundation, 2016). The region has been the third-largest oil and gas producer in the US between 1982 and 2013. Similarly, Oklahoma comes in the fifth position in

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[3] https://aoghs.org/oil-almanac/oklahoma-oil-history/

terms of the number of gas wells drilled (U.S. Energy Information Administration, 2015).

Oklahoma has experienced a surge in the disposal of wastewater from fracked wells due to a boom in fracking activity in the region (Apergis, 2019; Skoumal et al., 2015). On one hand, research has shown that O&G firms have provided substantial economic benefits to Oklahoma’s economy; however, a strand of literature attributes the rise in earthquakes in Oklahoma since 2006 to the wastewater injection in deep wells from fracking activities (Keranen et al., 2014; Rickman et al., 2017; Ng'ombe and Boyer, 2019; Rickman and Wang, 2020). The empirical evidence shows that earthquakes of approximately 4.0 or higher on the Richter scale are correlated with wastewater injection from fracking in Oklahoma (Holland and Gibson, 2011), with Holland (2013) also finding a strong association between earthquakes in Oklahoma and fracking activities.

Considering the above context, this paper investigates the impact of UNGD activities on the health profile of 76 counties across Oklahoma over the period 1998-2017 using an innovative analytical framework. We contribute to the growing literature on how fracking revolution affects the health outcomes to shed light on how this revolution affects the entire health profile of population across Oklahoma counties. To the best of our knowledge, this paper is one of the first studies to examine the effects of fracking on the entire health profile of the population across Oklahoma counties. We further the understanding of the role of UNGD activities in the US states, where economic incentives to increase investments in UNGD activities have been particularly strong. More specifically, by considering the health profile, the analysis documents that fracking revolution has had serious negative implications on the health profile of population across Oklahoma counties. Although the results are explicitly based on counties across Oklahoma, they could be also used with caution for policy perspectives in other US states experiencing similar fracking revolution.

The paper contributes through certain novelties. First, the empirical analysis employs five health indicators as a proxy for the health profile of a county: i) as the life expectancy of the population, ii) the mortality rate, iii) the number of deaths from all types of cancer per 100,000 people, iv) the number of deaths from cardiac failures per 100,000 people, and v) the number of deaths from respiratory-related problems per 100,000 people. This spatial analysis is significantly important because substantial new hydraulic fracturing operations are taking place in sparsely populated counties as well (Feyrer et al., 2017). Second, the empirical framework explicitly considers the role of demographic determinants (i.e., age, smoking, and race-ethnicity) on the health profile of counties across Oklahoma (McWilliams et al., 2009; Kar et al., 2016). The empirical set up allows the examination of the role carbon dioxide emissions from electric power plants can have in the health profile of the population (Driscoll et al., 2015; Buonocore et al., 2016). Furthermore, it considers the impact of seismic activity across Oklahoma states after 2006 (Hicks et al., 2018). Third, the dynamic panel data estimates are based on recently developed econometric methods that account for both observed and unobserved heterogeneity in panel data settings. To capture the impact of unknown common factors, the analysis employs Pesaran's (2006) innovative Common Correlated Effect (CCE) estimator. Furthermore, it uses GMM estimates to address potential short-run dynamics and endogeneity issues. Finally, the state-level assessment helps to understand the effects of energy on the state economy and their reflection on state budgetary impacts (Rickman and Wang, 2020).

Our main findings document that fracking poses significant risks to public health in Oklahoma. In particular, an increase in the number of (unconventional) wells has a positive impact on mortality rates, and incidences of cancer, cardiac, and respiratory diseases in communities in close spatial proximity; but has a negative impact on life expectancy. On average, a 1% increase in the number of fracking wells leads to a 4.2% reduction in life expectancy. Similar trends are observed with the remaining health indicators, where a 1% increase in the number of fracking wells leads to a 6.8% increase in the mortality rate, a 7.9% increase in cancer diseases, a 7.3% increase in cardiac diseases, and, finally, a 5.9% increase in respiratory diseases. Such findings provide some understanding into the cumulative effect of the fracking boom on the health profile of the population in Oklahoma and accordingly are expected to have implications for the national debate on the regulation of unconventional shale gas developments.

The remainder of the paper is organised as follows. Section 2 presents a brief review of the literature on the impacts of UNGD on public health. Section 3 lays out the methodology used to analyze the effects of UNGD on the health profile of Oklahoma counties. Section 4 describes the data used in the empirical analysis. Section 5 provides the empirical results and discussion of our findings, and, finally, Section 6 presents the summary and policy implications of our analysis.

2. Health effects of UNGD and the related literature

2.1. Background

Hydraulic fracturing (commonly known as fracking) procedure involves the injection of a mixture of water, sand, and chemicals at high pressure into layers of rock with the help of horizontal drilling. Fracking allows tapping unconventional tight oil and shale gas reserves previously believed to be commercially inaccessible (Ferreira et al., 2018). Fracking has been employed to produce crude oil in the US for more than 60 years.

Technological advancements in fracking have unleashed a 'shale boom' in O&G production in the United States (Feyrer et al., 2017).

Perhaps unsurprisingly, fracking has had a significant economic impact on the local economy. Feyrer et al. (2017) estimate that each additional million dollars of energy production generates $66,000 in wage income, $61,000 in royalty payments, and 0.78 jobs within the county. Further, the analysis documents that UNGD activities raised total US employment by 6.4 million and decreased aggregate unemployment rate by 0.43 during the Financial Crisis. Similarly, Bartik et al. (2019) illustrate that unconventional oil and gas development (fracking) leads to an increase in total income (3.3–6.1%), employment (3.7–5.5%), and salaries (5.4–11%). Additionally, local government revenues increased by 15.5%. According to Insight (2011) report, the UNGD industry contribution to GDP was more than $76 billion in 2010 and the industry supported 600,000 jobs in the same year. The report goes on to predict that, in 2035, the industry will contribute $231 billion towards the US GDP and will support over 1.6 million jobs.

Despite the economic benefits, fracking poses a significant risk to the health profile of communities living in proximity to such unhealthy activities. The extensive infrastructures of the fracking span across well developments, well completion and production, on-site and off-site processing, distribution, and storage of gas. As Gabrys (2017) notes, at every point in this infrastructure, both air and water degradation potentially occur. The wells drilled at initial extraction points generate greenhouse gases, like methane and air pollutants, including volatile organic compounds. The water and chemicals used to exert pressure to remove shale gas can lead to drinking and surface water contamination. The compressor sites (where gas is pressurised, refined, and pumped into pipelines) generate additional methane and volatile organic compound emissions in the form of benzene, toluene, ethylbenzene, and xylene, some of which are known carcinogens at even minute levels of exposure (Moore, 2013). As companies drill oil out of the shale buried deep below the earth, natural gases are also released. Often, these gases cannot be sold or processed and, therefore, are burned - a process known as flaring. This process produces local air pollutants like carbon dioxide and methane that are detrimental to local respiratory health (Blundell and Kokoza, 2020).

In short, hydraulic fracturing contributes to increased air and water pollution which affects both the physical and mental well-being of the populace living near the fracking sites. Therefore, the local community suffers from negative health implications in medium to long-run (Jahshan, 2015). Unsurprisingly, many researchers opine that the fracking industry is an uncontrolled health experiment on a colossal scale (Bamberger and Oswald, 2012).

2.2. Air pollution (and other nuisances, such as increased truck traffic)

Previous research has documented that shale gas developments contribute to increased concentrations of pollutants in the air which, in turn, lead to an increased risk of morbidity and mortality (Shonkoff et al., 2014; NRDC, 2014). McKenzie et al. (2012) estimate health risks for exposures to air emissions from an unconventional natural gas development project in Garfield County. The study suggests that sub-chronic exposures to air pollutants during well completion activities present the greatest potential for health effects. The study concludes that residents living within half amile radius of the well pad are at greater risk of negative health effects from the development than those living more than half a mile from the well pad.

A strand of literature documents a strong relationship between oil and gas emissions, the accumulation of air toxics, and the significant production of ozone in the atmospheric surface layer (Helmig et al., 2014). Likewise, researchers have demonstrated a positive association between ozone concentrations and clinic visits for adverse respiratory-related effects (Pride et al, 2015). Carpenter (2016) posits that fracking practices impose a number of significant threats to health due to air pollution from volatile organic compounds (which contain carcinogens such as benzene and ethyl-benzene) which, in turn, may have adverse neurologic and respiratory effects.

The largest source of methane emissions are natural gas and petroleum systems in the US (Meng, 2017). Karion et al. (2013) detect leakage of about 55,000 ±15,000 kg of methane per hour into the atmosphere in the Uinta Basin, which corresponds to 6.2–11.7% of the total natural gas production in this region. Petron et al. (2014) observe similar methane leakages in the Denver Basin (Colorado). Maduka and Tobin-West (2017) conduct a cross-sectional household survey among residents of 600 households in three gas-flaring and three non-gas-flaring host communities in the Niger Delta region of Nigeria. Results show that residents in a gas-flaring host community are 1.75 times more likely to be hypertensive than residents in non-gas-flaring communities. Blundell and Kokoza (2020) estimate the effect of flared natural gas on respiratory health in North Dakota. The authors employ a quasi-random variation in upwind flaring generated by the interaction of wind patterns and natural gas processing capacity. The study finds that a 1% increase in the amount of flared natural gas would increase the respiratory-related hospital visitation rate by 0.7%.

Levels of formaldehyde-a respiratory irritant-are also elevated around fracking sites due to truck traffic. McCoy and Saunders (2015) argue that one of the potential adverse impacts of truck traffic is road traffic accidents which can lead to potential spills of hazardous materials. Graham et al. (2015) examine the association between shale gas fracking and motor vehicle accident rates in Pennsylvania. The study shows that automobile and truck accident rates were between 15% and 65% higher in counties with fracking than their counterparts without such activities.

2.3. Risks to water resources

Vengosh et al. (2014) identify four potential risks to water resources resulting from fracking activities: i) the contamination of shallow aquifers with fugitive hydrocarbon gases, which can lead to the salinization of shallow groundwater through leaking natural gas wells and subsurface flow, ii) the contamination of surface water and shallow groundwater from spills, leaks and the disposal of inadequately treated shale gas wastewater, iii) the accumulation of toxic and radioactive elements in soil or stream sediments near disposal or spill sites, and iv) the over-extraction of water resources for high-volume hydraulic fracturing that could induce water shortages or conflicts with other water users, particularly in water-scarce areas.

Overall, the literature on the relationship between fracking and water contamination has produced inconclusive evidence so far. On one hand, researchers have documented that fracking poses a potential risk to water resources. For instance, Osborn et al. (2011) provide systematic evidence that shale-gas extraction in aquifers overlying the Marcellus and Utica shale formations of Northeastern Pennsylvania and Upstate New York caused methane contamination of drinking water. Jackson et al. (2013) examine 141 drinking water wells across the Appalachian Plateaus physiographic province of northeastern Pennsylvania. Results indicate methane detection in 82% of drinking water samples, with average concentrations six times higher for homes less than 1 km from natural gas wells. Ethane was 23 times higher in homes less than 1 km from gas wells and propane was detected in 10 water wells, all within approximately 1 km distance.

On the other hand, studies have suggested that methane in groundwater can be natural and unrelated to shale gas development (Molofsky et al. 2013; Baldassare et al., 2014). Through a country-level assessment, UPESA (2015) examines the potential effects of hydraulic fracturing on drinking water resources and identify various cases (i.e., Colorado, Creek, Killdeer and North Dakota) where inadequate design and the subsequent failure of well casing and/or cement have led to groundwater contamination. However, the number of identified cases was small as compared to the number of hydraulically fractured wells and, consequently, the study concludes that there is no evidence of widespread effects of fracking on drinking water resources in the US. Barth-Naftilan et al. (2018) incorporate time-series sampling of groundwater before, during, and after hydraulic fracturing, and the initiation of shale gas production within the Marcellus Shale. The study does not detect any groundwater impacts arising from the process of hydraulic fracturing. Instead, it discovers considerably temporal variability in methane concentrations in deeper horizons of freshwater aquifers and, consequently, attributed this to persistent shifts in the aquifer recharge that influence mixing between shallow freshwater and comparatively saline and methane-rich deep groundwater.

2.4. Impact on the physical and mental wellbeing of local communities

A strand of literature focuses on the negative health implication of UNGD activities on the health profile of the population in proximity to these developments in the US. Local communities have suffered from upper respiratory tract ailments, burning eyes, headaches, vomiting, and diarrhoea (Subra, 2010; McDermott-Levy and Kaktins, 2012; Werner et al., 2015). Likewise, UNGD activities have raised serious concerns about food safety given the potential exposure of farm animals to environmental contaminants from these developments (Bamberger and Oswald, 2012).

Fracking well density is associated with hospitalisation rates for the medical categories of dermatology, neurology, oncology, and urology in Pennsylvania (Jemielita et al., 2015). Using cross-sectional data on 97 adults living in Northeastern Colorado between October 2015 and May 2016, McKenzie et al. (2019) find that people living in the areas with the highest levels of oil and gas activity around their homes exhibited more signs of cardiovascular diseases (a higher augmentation index by about 6 per cent). Similarly, Denham et al. (2019) illustrate that long-term exposure to UNGD may have an impact on the prevalence of genitourinary and skin-related hospitalizations in the affected populations. Rasmussen et al. (2016) evaluate the relationship between UNGD activities and asthma exacerbations using a sample of 35,000 asthma patients. The study finds that proximity to fracking activities are strongly associated with an increased risk of mild, moderate, and severe asthma exacerbations. Furthermore, Colborn et al. (2011) find that numerous chemicals used during the fracking operations have long-term health effects. The study identifies 632 chemicals out of which more than 75% could affect the skin, eyes and other sensory organs, respiratory and gastrointestinal systems; 40-50% of the chemicals could affect the nervous system, immune and cardiovascular systems, and the kidneys; 37% could affect the endocrine system, and 25% could cause cancer and mutations.

People living near fracking sites have been exposed to various health hazards including carcinogens like benzene, which causes cancer and increases the risks of birth defects (McKenzie et al., 2014; McCoy and Saunders, 2015). Hill (2018) finds that an additional well is associated with a 7% increase in low birth weight, a 5-gram reduction in term birth weight and a 3% increase in premature birth and, consequently, conclude that shale gas development poses significant risks to human health. Casey et al. (2016) examine the impact of UNGD activities on birth outcomes using electronic health data on 10,946 birth records in Pennsylvania from January 2009 to January 2013. The results document a statistically significant relationship between maternal proximity to active fracking operations and premature births and high-risk pregnancies. Similarly, Currie et al. (2017) investigate records of more than one million births in Pennsylvania from 2004 to 2013. The study compares infants born to mothers living at different distances from active fracking sites and those born both before and after fracking was initiated at each site. Their study finds evidence for negative health effects (which include greater incidences of low-birth-weight babies and significant declines in average birth weight among various other measures of infant health) of in utero exposure to fracking sites within 3 km of a mother’s residence, with the largest health impacts seen for in utero exposure within 1 km of fracking sites.

Another strand of literature has suggested that fracking operations have caused higher infant mortality rates. For instance, Busby and Mangano (2017) find that fracking leads to a significant increase in mortality in the 10 counties where fracking activities were taking place in Pennsylvania. This could be an indication of private water well density and/or environmental law violations. In the context of Pennsylvania, McKenzie et al. (2017) find increased incidences of leukaemia in rural Colorado, whereas their findings have been contradicted by Fryzek et al. (2013). However, the latter study has been criticized on many fronts (Krupnick and Echarte, 2017). Firstly, it uses a very crude metric for exposure; secondly, the authors analyze cancer incidences in Pennsylvania counties for the time period 1995-2009, which was mostly before the fracking boom in the state; thirdly, the study ignores the issue of latency with cancer as fracking began in the state just one to two years before the endpoint of this study.

Horizontal drilling is also found to be deleterious for human well- being in Texas (Maguire and Winters, 2017). Likewise, Casey et al. (2018) report that UNGD activities cause adverse mental health and depression symptoms in Pennsylvania using the Patient Health Questionnaire-8 and electronic health record data among Geisinger adult primary care patients. Further, fracking operations are associated with nasal and sinus, migraine headache, and fatigue symptoms (Tustin et al., 2017).

2.5 Unconventional Oil and Gas Developments in Oklahoma

Oklahoma is one of the major contributors to oil and gas in the US. In 2019, Oklahoma was the fourth-largest crude oil producer among all the states accounted for nearly 5% of the country’s crude oil production. The state also had the fourth-largest gross withdrawals of natural gas across all US states in 2019 and accounted for about 9% of the nation's marketed production. The state is home to significant shale gas and coalbed methane resources, while it was the seventh-largest shale gas producer in the US in 2018 (U.S. Energy Information Administration, 2020). The economic importance of the oil and gas industry for the state cannot be overstated. In 2015, the industry employed 53,500 residents, while approximately 150,000 residents in total are either salary workers or self-employed. The household earnings from the industry amounted to $15.6 billion in 2015 which was 13.2% of total state earnings. Moreover, in the same year, average wages in the oil and gas sector ($104,000) were more than double the state average which was $44,178 (State Chamber of Oklahoma Research Foundation, 2016). Despite all the economic benefits this industry brings, as discussed above, the adverse health effects of fracking are well documented in the literature. Yet, the health effects of fracking activities in the context of Oklahoma have been largely ignored by the existing literature. The current study attempts to fill this gap in the literature.

3. Methodology

The objective of this study is to examine the effects of UNGD on health profile a sample of 76 counties across Oklahoma over the period 1998-2017. Based on the

Allanson and Petrie (2013) and Matthew and Brodersen (2018), we construct the long-run relationship between health profile and its potential determinates in the following manner:

$$\begin{aligned}\mathbf{lo\,g}(\boldsymbol{health_{it}}) = {} & \boldsymbol{\alpha_i} + \boldsymbol{\beta t} + \boldsymbol{b_1}\,\mathbf{log}(\boldsymbol{fd_{it}}) + \mathbf{b_2}\,\mathbf{log}(\mathbf{sd}_{it}) + \mathbf{b_3}\,\mathbf{log}(\mathbf{y}_{it}) + \mathbf{b_4}(\boldsymbol{Dmet}) \\ & + \mathbf{b_5}\,\mathbf{log}(\mathbf{age}_{it}) + \mathbf{b_6}(\mathbf{cigar}_{it}) + \mathbf{b_7}\,\boldsymbol{race_{it}} + \boldsymbol{b_8 D2006} + \boldsymbol{b_9 log}(\boldsymbol{grid_{it}}) \\ & + \boldsymbol{b_{10}}\,\mathbf{log}(\boldsymbol{transp_{it}}) + \boldsymbol{b_{11} log}(\boldsymbol{manuf_{it}}) \\ & + \boldsymbol{b_{12} u_{it}} + \boldsymbol{b_{13}}\ \mathbf{log}(\boldsymbol{bcr_{it}}) + \boldsymbol{b_{14}}\,\boldsymbol{educ_{it}} + \boldsymbol{b_{15}}\,\boldsymbol{DINJ} + \boldsymbol{\varepsilon_{it}} \qquad (\mathbf{1})\end{aligned}$$

where $health_{it}$ is the health profile of the county i, α_i denotes county fixed effects, βt represents time fixed effects, ε_{it} is error term and fd_{it} is the annual fracking (unconventional) activity. Our main objective is to explore the effects of fracking (fd_{it}) on the public health profile of counties ($health_{it}$) across Oklahoma. We use five health indicators as a proxy for the health profile of a county: i) as the life expectancy of the population, ii) the mortality rate, iii) the number of deaths from all types of cancer per 100,000 people, iv) the number of deaths from cardiac failures per 100,000 people, and v) the number of deaths from respiratory-related problems per 100,000 people.

The baseline regression in Equation (1) employs certain control variables. The list of control variables includes: (i) annual county non-fracking (conventional) activity (sd_{it}) to capture the different dynamics the two methods may have on the health profile (Wachtmeister and Höök, 2020), (ii) a set of counties' economic factors, such as real personal income measured as households' personal income of each county (y_{it}), unemployment rate per county ($\mathrm{u_{it}}$), and bank credit per county ($\mathrm{bcr_{it}}$), (iii) dummy indicator for whether a county is a metro or non-metro area – 1 if metro, 0 when a county is non-metro ($Dmet$), (iv) average age of the population in a county (age_{it}), (v) the percentage of adults who smoke cigarettes per year (cigar_{it}), (vi) the percentage of county population considered as non-white (i.e., Black, Asian, Others) ($race_{it}$), (vii)a variable that explicitly considers the year 2006 where unconventional activities became widespread in Oklahoma (Apergis, 2019), (viii) electricity grid access (access to an interconnected network that delivers electricity to consumers) $(grid_{it})$, (ix) transportation infrastructure measured as the length of the transportation network (i.e., kilometres of the road network) $(transp_{it})$, (x) the air pollution levels originated from the manufacturing sector $(manuf_{it})$, and xi) the education variable (*educ*) measured as the percentage of people with a high school degree or higher per county.

The role of demographic determinants, such as age, the percentage of adults who smoke cigarettes, and race-ethnicity has long been signified as the primary drivers in the health literature, on the grounds that they imply different impacts on the risks associated with certain health indicators, as well as certain groups of the population (McWilliams et al., 2009; Kar et al., 2016). The model includes three different types of economic factors that impact health indicators, personal income, unemployment, and bank credit, per county. Khan et al. (2016) carry out a study on the role of economic factors that determine health in national and local levels. They provide evidence that certain economic drivers, such as income and total bank credit, could be used to encourage the use of healthy patterns of consumption, and can support individuals to meet their needs, as well as encourage incentives that can be used to alter provider and patients' behaviour. For instance, total bank credit can help to increase income, by supporting people to experience higher wellbeing levels. Supportive health-related financial drivers could help householders not only to increase their income but also to manage healthcare-related financial risks. The literature has also provided evidence in favour of a significant effect of unemployment on health, usually through the channel of the unemployment hypothesis (Backhans and Hemmingsson, 2012; Gagin & Shinan-Altman, 2012), although it affects people differently, depending on factors, such as gender and age (Backhans and Hemmingsson, 2012; Gagin & Shinan-Altman, 2012; Malat and Timberlake, 2013). The hypothesis is that unemployment per se creates unequal health conditions in young people (and specifically males) in the sense that it often leads to specific behaviours which are detrimental to health. Moreover, basic education is an integral part of being healthy. A person is unhealthy if he or she lacks basic knowledge, the ability to reason, emotional capacities of self-awareness and emotional regulation, and skills of social interaction. These embodied personal attributes or mental capacities, the products of formal education, as well as other learning experiences, are conceptually comparable to physical capacities of fitness and coordination – well-established components of health (Ross and Wu, 1995; Egerter et al., 2009).

In terms of the variables of electricity grid access and air pollution, the literature has emphasized the impact of associated carbon dioxide emissions from electric power plants on the health profile of the population due to the degradation of air pollution quality (Driscoll et al., 2015; Buonocore et al., 2016). Given that transportation infrastructure is a critical ingredient in economic development at all levels of income, supporting personal well-being and economic growth, the literature has supported that it has substantial health hazards for public investments in health and hospital services (Evans and Karras, 1994).

Finally, given the significant increase in seismic activity in Oklahoma state, especially after 2006, along with the potential environmental and public health risks at stake, attributed to Class II injection well volumes (Hicks et al., 2018), the analysis makes use of the dummy variable DINJ which explicitly considers the type of injection wells used in the drilling activities across counties. It takes the value of one if the drilling well is of an injection type, and zero otherwise. Injection describes a method where deep fracking wastewater is injected into the ground.

Our empirical setup, based on a panel time-series approach, can be justified for several reasons (Eberhardt and Teal, 2011). First, we know that many variables under study are nonstationary. Therefore, the standard OLS regressions can produce spurious estimates in the presence of nonstationary variables. Consequently, we need to be extremely careful in estimating the long-run estimates based on standard procedures. However, we can test for cointegration to check whether we can establish long-run equilibrium relationships in the data. We can find cointegration among our variables under study when regressions yield stationary residuals. The practical indication of spurious regression will be nonstationary residuals. Our choice of the panel framework allows us to exploit the individual information on all Oklahoma counties and their time-series data in a comparative setting while accounting for this spurious regression concern. Second, our panel time-series approach incorporates a large degree of flexibility and allows for parameter heterogeneity across counties in the short-run dynamics.

Econometrically, we are aware that pooled ordinary least squares estimator (OLS) can lead to inconsistent estimates and bias estimates when the errors of a panel regression are cross-sectionally correlated but are ignored in the panel regression (Phillips and Sul, 2003). Therefore, we employ Common Correlated Effects (CCE) estimator that accounts for both observed and unobserved heterogeneity (Pesaran, 2006) to estimate the long-run relationship between the health profile and its determinants, described by Equation (1). Pesaran (2006) adopts a multifactor residual model, such as:

$$\begin{aligned} log\ (health_{it}) = {} & \alpha_i + \beta t + b_1 \log(fd_{it}) + \mathrm{b}_2 \log(\mathrm{sd}_{it}) + \mathrm{b}_3 \log(\mathrm{y}_{it}) + \mathrm{b}_4(Dmet) \\ & + \mathrm{b}_5 \log(\mathrm{age}_{it}) + \mathrm{b}_6(\mathrm{cigar}_{it}) + b_7 \log(race_{it}) + b_8 D2006 + b_9 log(grid_{it}) \\ & + b_{10} \log(transp_{it}) + b_{11} log(manuf_{it}) + b12\ unit + b13\ log\ (bcrit) \\ & + b14\ educit + b15\ DINJ + \eta_{it} \end{aligned}$$

$e_{it} = \lambda'_i F_t + u_{it}$ (2)

where subscript (it) is the ith cross section observation at time t, for t = 1,2, …, T and i = 1,2, , … N. F_t is the mx1 vector of unobserved common factors. Pesaran (2006) considers the case of weakly stationary factors. To deal with potential residuals' cross section dependence, Pesaran (2006) uses cross sectional averages, as observable proxies for common factors F_t. Slope coefficients, as well as their means, can be consistently estimated within the following auxiliary regression:

$\log(health_{it}) = \alpha_i + \beta\ t + b_1 \log(fd_{it}) + b_2 \log(sd_{it}) + b_3 \log(y_{it}) + b_4\ Dmet + b_5 \log(age_{it})$
$b_6\ (cigar_{it}) + b_7 \log(race_{it}) + b_8\ D2006 + b_9 \log(grid_{it}) + b_{10} \log(transp_{it}) +$
$b_{11} \log(manuf_{it}) + b_{12}\ un_{it} + b_{13} \log(bcr_{it}) + b_{14}\ educ_{it} + b_{15}\ DINJ +$
a_1
$\log(\overline{fd}_t) + a_2 \log(\overline{sd}_t) + a_3 \log(\overline{y}_t) + a_4 \log(age_t) + a_5\ cigar_t + a_6 \log(race_t) +$

$a_7 \log(\overline{grid}_t) + a_8 \log(\overline{transp}_t) + a_9 \log(\overline{manuf}_t) + a_{10}\ \overline{u}_t + a_{11}\ \overline{bcr}_t + a_{12}\ \overline{educ}_t + \varepsilon_{it}$ (3)

where a bar above a variable indicates the average of it. The 'Common Correlated Effects Mean Group' (CCEMG) estimator is the average of the individual CCE estimators $ß_{j,CCE}$:

$$ß_{CCEMG}: 1/N \sum_{j=1}^{N} ß_{j,CCE}$$

The new CCEMG estimator follows asymptotically the standard normal distribution.

Specifically: $\sqrt{N}\ (ß_{CCEMG,i} - \beta_i) \rightarrow N(0, \Sigma_{MG})$ (4)

In a series of Monte Carlo experiments, Pesaran (2006) shows that the CCE estimators have the correct size, while they have better small-sample properties than alternatives that are available in the literature. Moreover, the small-sample properties of the CCE estimators are not much affected by the residual serial correlation of the errors.

4. Data

We study the effects of Unconventional Natural Gas Development (UNGD) on a variety of human health-related outcomes across Oklahoma counties. We assembled annual dataset including panel observations from 76 Oklahoma counties, over twenty years (1998-2017). The dataset does not include the Adair county, because nofracking wells have been activated in this territory. The empirical analysis makes use of the primary control variable which provides the number of drilled oil and natural gas wells using fracking technologies. Moreover, data on the number of drilled oil and natural gas wells using non-fracking (conventional) technologies are also obtained. Data on these variables are obtained from the Oil and Gas Division of the Oklahoma Corporation Commission (http://www.occ.state.ok.us/OG/ogoe.htm). Data on county income (measured as households' personal income of each county) and total bank credit per county variables, were retrieved from the Bureau of Economic Analysis (BEA) database, while the data on unemployment were sourced from the Bureau of Labour Statistics. Data on the educational variable, measured as the percentage of the population with a high-school degree and above, were obtained from the US Census Bureau.

The analysis uses data of age and race based on the American Community Survey (ACS) database provided by the US Census Bureau. The data on cigarettes, measured as the percentage of adults who smoke cigarettes every day or some days, come from the Kaiser Family Foundation analysis of the Centers for Disease Control and Prevention (CDC)'s Behavioral Risk Factor Surveillance System (BRFSS). Percentages are weighted to reflect population characteristics, while data are based on the Behavioral Risk Factor Surveillance System, an ongoing, state-based, random-digit-dialled telephone survey of non-institutionalized civilian adults aged 18 years and older. Data on population characteristics are based on the ACS database (2005-2017), US census 2000 (2000-2004), and the US census 1990 (1998-1999). Data on the access to electrical grids (measured as electricity consumption) come from the U.S. Department of Energy's Energy Information Administration. This type of electricity consumption consists of retail sales plus direct use of electrical energy; it is equivalent to the next generation in the electric power, commercial, and industrial sectors, plus net electrical imports, minus losses from transmission and distribution and unaccounted-for causes. Data on transportation infrastructure, measured as the amount of federal and state expenditure on highways and parking facilities, have been extracted from the Centre of Budget and Policy Priorities. Finally, data on air pollution levels come from the US Environmental Protection Agency website (https://www.epa.gov/outdoor-air-quality-data) and are measured through the Air Quality Index (AQI). Higher values of the index indicate higher quality and vice versa.

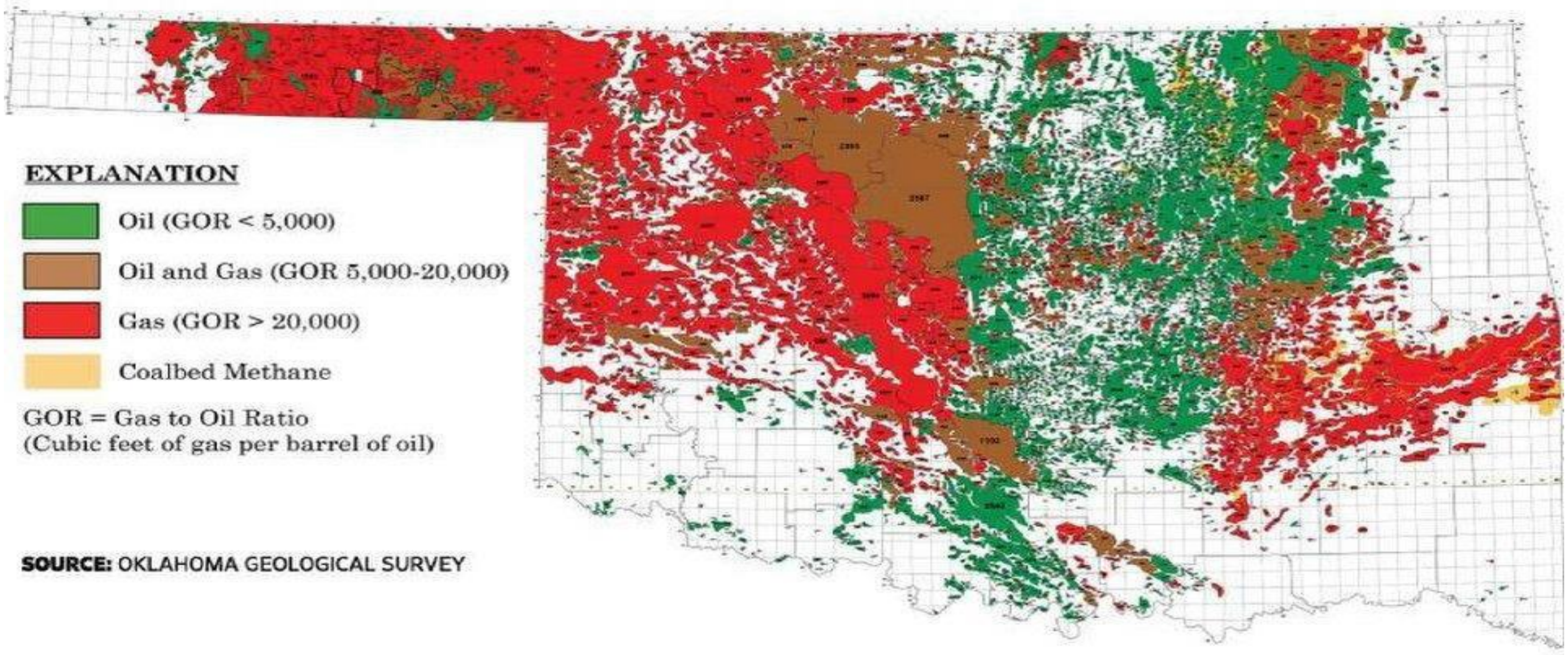
Data on life expectancy and mortality rates for Oklahoma state are obtained from the Institute for Health Metrics and Evaluation (IHME) at the University of Washington (http://www.healthdata.org/) which analyzes the performance of all 3,142 US counties. Life expectancy is measured in years, while mortality rates are measured as the number of deaths, scaled to the size of a population, per unit of time. It is expressed in units of deaths per 100,000 individuals per year. Data on cancer diseases are obtained from the Cancer Statistics Center (American Cancer Society) and indicates the number of deaths from any cancer disease per 100,000 individuals per year. Cardiac disease data are obtained from America's Health Rankings analysis of CDC WONDER Online Database, which also provides data on the number of deaths from cardiovascular diseases. Finally, data on respiratory diseases are obtained from the National Center for Health Statistics (from the US Center for Disease Control and Prevention). Table 1 reports the definition, notation and descriptive statistics of the variables under study. We can also note that during the post-2006 period, the threshold year when the state experienced a strong boom in fracking activities, all health indicators have deteriorated, which strongly motivates us to formally explore whether fracking activities can be held potentially responsible for such a worsening performance. Figure 1 provides a picture map of oil and natural gas wells across the state, while Figures 2 shows the number of fracking and conventional oil and natural gas wells overtime under consideration.

Table 1

Descriptive statistics (Annual observations)

Variables	**Notation**	**Definition**	**Mean**	**S.D.**	**Min**	**Max**
Life expectancy	$health_{it}$	The life expectancy of the population in a county	72.45	21.40	69.31	75.66
Life expectancy prior to 2006			72.96	19.88	70.84	76.81
Life expectancy after 2006			71.98	22.75	71.59	76.14
Mortality rate	$health_{it}$	The mortality rate	10.15	18.24	6.01	24.76
Mortality rate prior to 2006			9.13	15.49	5.73	22.19
Mortality rate after 2006			10.61	19.88	6.37	26.71
Cancer diseases	$health_{it}$	The number of deaths from all types of cancer per 100,000 people	178.43	55.65	41.90	469.60
Cancer diseases prior to 2006			167.81	51.39	37.69	442.57
Cancer diseases after 2006			186.47	58.62	45.81	487.93
Cardiac diseases	$health_{it}$	The number of deaths from cardiac failures per 100,000 people,	232.06	78.77	51.30	576.20
Cardiac diseases prior to 2006			204.58	76.51	45.92	528.84
Cardiac diseases after 2006			249.73	81.09	55.62	590.72
Respiratory diseases	$health_{it}$	The number of deaths from respiratory-related problems per 100,000 people	13.32	5.94	0.00	67.10
Respiratory diseases prior to 2006			11.74	5.48	0.00	58.91
Respiratory diseases after 2006			15.88	6.14	13.68	76.58

Fracking wells	fd_{it}	The number of drilled oil and natural gas wells using fracking (unconventional) technologies	1830.64	4230.67	98.00	36731.00
Fracking wells prior to 2006			317.38	294.55	98.00	475.00
Fracking wells after 2006			3452.81	5409.74	2150.00	43053.00
Non-fracking wells	sd_{it}	The number of drilled oil and natural gas wells using non-fracking (conventional) activity	2027.49	4179.82	596.00	32469.00
Income	y_{it}	A county's real personal income measured as households' personal income	$37,332.39	$98684.63	$14,883.00	$78,643.00
Metro dummy	$Dmet$	Dummy indicator: 1 if a county is metro, 0 when non-metro	0.77	0.36	0	1
Age	age_{it}	The average age of the population in a county	49.29	1.94	37.00	55.00
Cigarettes (%)	cigar_{it}	The percentage of adults who smoke cigarettes per year	21.94	1.39	17.50	25.40
Non-white population	$race_{it}$	The percentage of county population considered as non-white (i.e., Black, Asian, Others)	22.76	11.68	18.59	27.83
Grids (megawatt hours)	$grid_{it}$	electricity grid access	42258123.00	2784129.00	29895663.00	89567329.00
Expenditures on roads	$transp_{it}$	Transportation infrastructure measured as the length of the transportation network (i.e., kilometres of the road network	21774983.00	126459.00	12895452.00	34882906.00
Manufacturing air pollution	$manuf_{it}$	The air pollution levels originated from the manufacturing sector	52.00	12.39	41.00	67.00
Unemployment rate	u_{it}	The unemployment rate across all counties	4.7	1.06	3.20	7.10
Bank credit	bcr_{it}	Total bank credit across all counties (thousands of dollars)	9,622,616	1,598,899.93	7,535,639	12,836,748
Education	$educ_{it}$	Percentage of population with a high-school degree and better	78.24	25.69	69.52	89.74



SOURCE: OKLAHOMA GEOLOGICAL SURVEY

Fig 1. Oklahoma map of oil and natural gas wells.

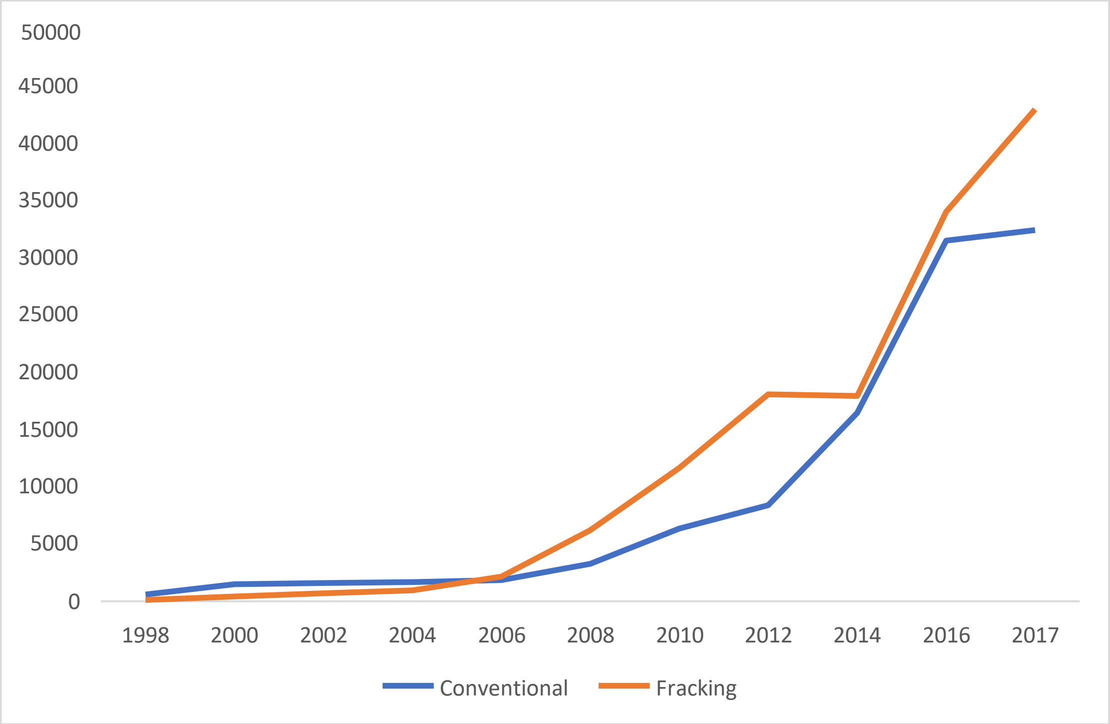


Fig 2. Conventional and fracking oil and natural gas wells (1998-2017)

5. Empirical analysis

We know that when variables under study are non-stationary the analysis will provide unreliable estimates for the impact of fracking on health profile. We start our empirical by presenting tests for the stationarity of all variables in the data following Pesaran (2007) CIPS test (H_0: the series is nonstationary). The analysis also performs two bootstrap panel unit root tests proposed by Smith et al. (2004). The results in Table 2 provide a strong indication that all variable series in the data are nonstationary, but all variables in the first difference series are stationary.

Table 2

Panel unit roots

	Pesaran CIPS test	Smith et al. t-test	Smith et al. LM-test	Pesaran CIPS test	Smith et al. t-test	Smith et al. LM-test
Variables	Level			First Difference		
Fracking	-1.26	-1.4	2.73	-5.84***	-6.81***	23.95***
Non- fracking	-1.29	-1.43	2.69	-6.18***	-7.12***	24.75***
Income	-1.36	-1.44	2.94	-5.92***	-6.71***	26.46***
Grids	-1.24	-1.31	2.73	-6.05***	-6.38***	29.82***
Transport.	-1.35	-1.39	2.42	-6.24***	-6.40***	28.74***
Manuf.	-1.31	-1.4	2.67	-6.29***	-6.45***	30.18***
Lifeexp	-1.39	-1.43	2.84	-6.14***	-6.30***	25.47***
Mortality	-1.41	-1.29	3.04	-5.88***	-6.52***	25.48***
Cancer	-1.38	-1.38	2.91	-6.29***	-6.48***	26.32***
Cardiac	-1.22	-1.46	3.12	-6.58***	-6.94***	25.49***
Respir	-1.35	-1.37	3.09	-6.19***	-6.47***	24.38***
Age	-1.45	-1.48	3.14	-5.84***	-5.93***	18.74***
Cigar	-1.28	-1.32	2.97	-6.93***	-7.54***	24.09***
Race	-1.35	-1.38	2.79	-6.86***	-7.42***	23.49***
Unemployment rate	-1.28	-1.34	2.68	-6.41***	-6.75***	22.61***
Bank credit	-1.35	-1.40	2.61	-6.57***	-6.88***	24.98***
Education	-1.38	-1.42	2.58	-6.48***	-6.77***	23.71***

Notes: Rejection of the null hypothesis indicates stationarity. *** *** indicate rejection of the null hypothesis of non-stationarity at 1%.

Given the variables in the data are integrated of order one, the next step is, then, to use panel cointegration to explore if one or more linear combinations of the variables under study are cointegrated. We adopt Westerlund (2008) to analyze the presence of cointegration between the health profile and its potential determinants. We use two Durbin–Hausman panel cointegration tests - the panel test (DH_{group}) and the group mean test (DH_{panel}) (H_0: no cointegration of health profile and its potential fundamentals series). These tests are applied under generic conditions as they do not rely heavily on a priori knowledge of the integration order of the variables included in the models. Furthermore, DH_{group} and DH_{panel} tests account for cross-sectional dependence where the error term in Equations (1) is obtained by idiosyncratic innovations and unobservable factors that are common across units of the panel (Auteri and Constantini, 2005).

Table 3 presents two cointegration test results based on Westerlund (2008). Models 1 to 5 report the cointegration results for each of the five alternative health indicators under study. Considering Table 3, the null hypothesis of no cointegration is rejected at 1% significance across five model specifications by both DH_{panel} and DH_{group} statistics. Our results establish the presence of a long-run equilibrium (cointegration) among health profile and its potential determinants, a described in Equation (1).

Table 3

Westerlund’s panel cointegration tests

Tests	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
	Life Expectancy	**Mortality Rate**	**Cancer Diseases**	**Cardiac Diseases**	**Respiratory Diseases**
DH_{group}	9.953^{***}	10.908^{***}	11.116^{***}	12.568^{***}	10.084^{***}
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
DH_{panel}	15.095^{***}	14.952^{***}	15.854^{***}	17.772^{***}	14.883^{***}
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]

Note: The group mean statistics DHgroup is calculated by multiplying n individual terms before summing them together. However, the panel statistic DHpanel is constructed first summing the various terms and then multiplying. Figures in brackets denote p-values. The criterion used is IC2(K) with the Maximum number of factors (K) set equal to 6. For the bandwidth selection, M is chosen to re-present the largest integer less than 4(T/100)2/9, as suggested by Newey and West (1994). ***: $p \leq 0.01$.

Table 4 presents our panel time-series estimates of Equation (1) derived from common correlated effects mean group (CCE-MG) estimator imposing parameter homogeneity across counties. We report estimates for five specifications, where each model represents a particular health indicator: i) life expectancy, ii) the mortality rate, iii) cancer diseases, iv) cardiac diseases, and v) respiratory diseases as the dependent variable, respectively.

In Model 1 we start with life expectancy specification regressing fracking on life expectancy. In this specification, the coefficient of fracking b_1 appears to be significantly negative. Our findings document a strong negative impact of fracking activities on life expectancy in Oklahoma. On average, a 1% increase in the number of fracking wells lead to a 4.1% reduction in life expectancy. Given the average number of all fracking wells across counties in Oklahoma, a 1% increase implies 18.3 wells that use the fracking method in drilling out oil and natural gas. Furthermore, the findings in Table 4 (Model 2 - 5) provide strong evidence of the positive effect of fracking activities on the mortality rates, and incidences of cancer, cardiac, and respiratory diseases. More specifically, a 1% increase in the number of fracking wells is expected to lead to a 6.4% increase in the mortality rate, a 7.5% increase in cancer diseases, a 7.0% increase in cardiac diseases, and finally a 5.5% increase in respiratory diseases.

Overall, our results in Table 4 are consistent with the literature in showing that the fracking is negatively and significantly associated with adverse health outcomes i.e., cancer incidence, asthma, hospitalizations, mortality from traffic accidents (see Deziel et al., 2020 for a recent survey). For example, the findings on cardiac diseases are consistent with that of McKenzie et al. (2019) who also show that higher levels of oil and gas activities in the local areas are associated with a higher frequency of symptoms of cardiovascular diseases in the context of Colorado. Jemielita et al. (2015) also examine an association between wells and healthcare use by zip code from 2007 to 2011 in Pennsylvania and conclude that cardiology inpatient prevalence rates were significantly associated with the number of wells per zip code. The findings on UNGD-induced respiratory illness lend support in Rasmussen et al. (2016) who evaluate the relationship between UNGD activities and asthma exacerbations (respiratory disease) using data from Pennsylvania and find that proximity to fracking activities is strongly associated with increased risks of mild, moderate, and severe asthma exacerbations. The finding that there is a positive correlation between UNGD activities and cancer incidence, is consistent with the findings provided by Finkel (2016) who report an increase in the standardised incidence ratio of urinary bladder cancer in southwestern Pennsylvania as fracking activities intensified in the region.

Table 4 shows that the coefficients of non-fracking activities bear the same sign as the fracking activities, however, they are not statistically significant at the 10% level in Model 1, 3, 4 and 5, except for the specification in Model 2. Moreover, Wald tests recommended by Wolak (1989) cannot reject the null hypothesis that the b_1 coefficient is greater than the b_2 coefficient, implying that the impact of fracking activities on health is stronger than the non-fracking activities. Considering these results, we do find evidence of any significant negative impact of non-fracking wells on the health profile of the population across Oklahoma counties, (except in Model (2) where the health indicator is measured as the mortality rate; even then the statistical significance is very marginal, only at 10%). These findings are complementary to our results above, suggesting the strong negative effects of fracking drilling wells only on several health indicators across Oklahoma.

Income has a significant, negative impact on four measures of health profile (i.e., mortality rates, and incidences of cancer, cardiac, and respiratory diseases) and a positive impact on life expectancy when we consider all the counties over the period 1998-2017 (Table 4). Our results imply that wealthy people live longer and experience lower incidences of cancer, cardiac, and respiratory diseases, on average, when compared to people with lower income levels (Hirdes et al., 1986; Mullis, 1992; Case et al., 2002). A rise in smoking (cigars) has a positive impact on mortality rates, and incidences of cancer, cardiac, and respiratory diseases in communities in close spatial proximity, but has a negative effect on life expectancy, aligning with the existing literature (Vogl et al., 2012; Jha and Peto, 2014). Moreover, increased energy consumption is associated with lower life expectancy, higher mortality rates, incidences of cancer, cardiac, and respiratory diseases (Ezzati and Kammen, 2002; Wang, 2010). Electricity consumption contributes to air pollution which not only exerts a substantial effect on established health endpoints, but it is also associated with broader numbers of disease outcomes. The dummy variable (D2006) has a negative impact on life expectancy and a positive on the other four indicators of health outcome, confirming the detrimental effects of such unconventional oil and natural gas developments on public health (Apergis, 2019).

In terms of the remaining drivers of health profile, the findings clearly indicate that age has a negative effect on mortality rates, incidences of cancer, cardiac, and respiratory diseases, and a negative effect on life expectancy. Similarly, race (the percentage of non-white population) has a negative impact on life expectancy and a positive effect on the remaining four health indicators. Furthermore, higher (lower) expenditures on transportation infrastructure have a positive effect on life expectancy and a negative one in the remaining health variables, while better air quality improves life expectancy and has detrimental effects on mortality and on the disease variables. (Lepeule et al., 2012; Meister et al., 2012; Jedrychowski et al., 2013; Proietti et al., 2013; Kelly and Fussell, 2015). Unemployment exerts a negative effect on life expectancy and a positive effect on the remaining definitions of health, while bank credit impacts positively life expectancy and negatively the remaining health indicators, with education exerting a positive effect on life expectancy and a negative impact on the remaining definitions of the health profile of the population. Finally, the injection well dummy exerts a negative effect on life expectancy, as well as a positive impact on the remaining health indicators.

Table 4

Common correlated effects mean group (CCE-MG) estimates: 1998-2017

	Model 1 **Life expectancy**	**Model 2** **Mortality Rate**	**Model 3** **Cancer Diseases**	**Model 4** **Cardiac Diseases**	**Model 5** **Respiratory Diseases**
Constant	-0.432**	0.363*	-0.385*	-0.328*	-0.313*
	[0.05]	[0.08]	[0.06]	[0.09]	[0.10]
log(fracking)	-0.041***	0.064***	0.075***	0.070***	0.055***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
log(nonfrack)	-0.015	0.028*	0.019	0.022	0.016
	[0.19]	[0.10]	[0.15]	[0.15]	[0.22]
log(grid)	-0.020*	0.022*	0.026*	0.014	0.015
	[0.10]	[0.09]	[0.07]	[0.18]	[0.20]
log(transport)	0.023*	-0.028*	-0.005	-0.025*	-0.031**
	[0.09]	[0.08]	[0.31]	[0.08]	[0.05]
log(manuf.)	0.044**	-0.038**	-0.027*	-0.031*	-0.040**
	[0.02]	[0.04]	[0.07]	[0.06]	[0.03]
log(income)	0.075***	-0.056***	-0.045***	-0.054***	-0.050***
	[0.00]	[0.00]	[0.01]	[0.00]	[0.00]
D_{met}	-0.046***	0.042***	0.038**	0.041***	0.039**
	[0.00]	[0.01]	[0.03]	[0.01]	[0.02]
log(age)	-0.045***	0.068***	0.054***	0.052***	0.060***
	[0.01]	[0.00]	[0.00]	[0.00]	[0.00]
log(cigar)	-0.050***	0.057***	0.084***	0.090***	0.098***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
log(race)	-0.042***	0.070***	0.074***	0.062***	0.050***
	[0.01]	[0.00]	[0.00]	[0.00]	[0.00]
un	-0.062***	0.054***	0.069***	0.073***	0.028
	[0.00]	[0.00]	[0.00]	[0.00]	[0.15]
log(bcr)	0.055***	-0.063***	-0.039*	-0.048**	-0.024
	[0.00]	[0.00]	[0.09]	[0.03]	[0.18]
educ	0.084***	-0.072***	-0.078***	-0.096***	-0.062***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
D2006	-0.082***	0.093***	0.075***	0.083***	0.101***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
DINJ	-0.052***	0.048***	0.077***	0.064***	0.071***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
R^2-adjusted	0.70	0.73	0.76	0.71	0.70
Wald test	[0.01]	[0.01]	[0.01]	[0.02]	[0.01]
County fixed effects	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES

Figures in brackets denote p-values. Wald tests check the null hypothesis that the fracking activities coefficient is greater than the non-fracking activities coefficient. ***: $p \leq 0.01$; **: $p \leq 0.05$; *: $p \leq 0.10$.

To address the issue of potential endogeneity, the analysis re-estimates the findings obtained in Table 4, by making use of the general Method of Moments (GMM) methodology which explicitly avoids potential endogeneity and is based on the approach recommended by Arrelano and Bover (1995) and Blundell and Bond (1998). It is worth emphasising that endogeneity is not exclusively focusing on potential causality between health and fracking activities, but also on causality links between health and any of the control variables. For instance, in terms of the relationship between health and income growth, the role of health in economic growth is one of the best-known relations in the growth process (Bloom and Canning, 2000). Healthy populations increase labour productivity and per capita income. The literature has indicated that there have been three main mechanisms that disease impedes economic wellbeing and development: i) avoidable disease reduces the number of years of healthy life expectancy, ii) the effect of disease on parental investments in children, and iii) the depressing effects of disease on the returns to business and infrastructure investments, beyond the effects on individual labour productivity. In this context, the literature has developed models where health is incorporated in traditional growth models (Howitt, 2005; Van Zon and Muysken, 2005; Weil, 2007). Moreover, empirical studies document that health conditions can explain labour market transitions. In particular, Stewart (2001) highlights the impact of health on the duration of unemployment, and Garcia-Gomez et al. (2010) shows that health impacts on exits out of and entries into employment. Additionally, other studies provide evidence that poor health affects everyone’s labour choices, with the impact being especially powerful among the elderly (Cai and Kalb, 2006; Christensen and Kallestrup and Lamb, 2012). In addition, a study by Chatterji et al. (2017) signifies that the impact of a person’s health varies with the type of health deterioration, i.e. chronic diseases, such as cancer, diabetes, mental illness, and disabilities seem to have the strongest effect on individual transitions in the labour market.

The new findings are reported in Table 4a. They clearly highlight the presence of similar estimates as above. Moreover, the table reports relevant diagnostics. For the validity of the instruments, the results need to reject the test for second-order autocorrelation, AR(2), in the error variances. It is evident that the AR(2) test fails to reject the respective null. Thus, the test supports the validity of the instruments used. Table 4a also reports the Hansen test for overidentifying restrictions. In the estimation process, a range from 18 to 21 instruments have been used. As the number of instruments was by far lower than the number of observations, this did not create any identification problem, as reflected in the Hansen test.

Table 4a

GMM estimates: 1998-2017

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
	Life expectancy	**Mortality Rate**	**Cancer Diseases**	**Cardiac Diseases**	**Respiratory Diseases**
Constant	-0.0419**	0.0379*	-0.0401**	-0.0366*	-0.0338*
	[0.05]	[0.07]	[0.05]	[0.07]	[0.09]
Δlog(fracking)	-0.0049***	0.0070***	0.0078***	0.0075***	0.0062***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
Δlog(fracking)$_{-1}$	-0.0034**	0.0048***	0.0054***	0.0051***	0.0042**
	[0.04]	[0.01]	[0.00]	[0.00]	[0.02]
Δlog(nonfrack)	-0.0029	0.0037*	0.0024	0.0026	0.0019
	[0.15]	[0.09]	[0.14]	[0.13]	[0.20]
Δlog(nonfrack)$_{-1}$	-0.0014	0.0020	0.0012	0.0013	0.0011
	[0.24]	[0.14]	[0.19]	[0.18]	[0.20]
Δlog(grid)	-0.0025*	0.0026*	0.0030*	0.0018	0.0021
	[0.09]	[0.08]	[0.07]	[0.14]	[0.12]
Δlog(transport)	0.0027*	-0.0034*	-0.0012	-0.0032*	-0.0037**
	[0.08]	[0.06]	[0.26]	[0.07]	[0.05]
Δlog(manuf.)	0.0048**	-0.0041**	-0.0032*	-0.0036**	-0.0047**
	[0.02]	[0.03]	[0.06]	[0.05]	[0.02]
Δlog(manuf)$_{-1}$	0.0032**	-0.0027*	-0.0021*	-0.0022*	-0.0033*
	[0.05]	[0.08]	[0.10]	[0.10]	[0.06]
Δlog(income)	0.0078***	-0.0062***	-0.0051***	-0.0059***	-0.0058***
	[0.00]	[0.00]	[0.01]	[0.00]	[0.00]
Δlog(income)$_{-1}$	0.0055***	-0.0047**	-0.0039*	-0.0046**	-0.0042**

	[0.00]	[0.02]	[0.06]	[0.04]	[0.05]
D_{met}	-0.0049***	0.0045***	0.0044**	0.0047***	0.0043**
	[0.00]	[0.01]	[0.02]	[0.01]	[0.02]
Δlog(age)	-0.0049***	0.0073***	0.0058***	0.0059***	0.0066***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
Δlog(cigar)	-0.0054***	0.0062***	0.0088***	0.0094***	0.0104***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
Δlog(race)	-0.0046***	0.0073***	0.0079***	0.0066***	0.0057***
	[0.01]	[0.00]	[0.00]	[0.00]	[0.00]
Δun	-0.0068***	0.0059***	0.0074***	0.0078***	0.0032
	[0.00]	[0.00]	[0.00]	[0.00]	[0.12]
Δlog(bcr)	0.0059***	-0.0066***	-0.0043*	-0.0054**	-0.0029
	[0.00]	[0.00]	[0.07]	[0.02]	[0.15]
$\Delta\log(bcr)_{-1}$	0.0043**	-0.0050**	-0.0029	-0.0038*	-0.0014
	[0.03]	[0.02]	[0.12]	[0.08]	[0.21]
Δeduc	0.0088***	-0.0075***	-0.0083***	-0.0104***	-0.0068***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
D2006	-0.0085***	0.0096***	0.0079***	0.0086***	0.0107***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
DINJ	-0.0060***	0.0068***	0.0084***	0.0089***	0.0103***
	[0.00]	[0.00]	[0.01]	[0.00]	[0.00]
R^2-adjusted	0.72	0.76	0.77	0.73	0.74
Wald test	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
County fixed effects	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES
AR(1)	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
AR(2)	[0.51]	[0.48]	[0.54]	[0.59]	[0.47]
Hansen test	[0.58]	[0.63]	[0.61]	[0.58]	[0.64]
No. of instruments	18	19	18	20	21

Figures in brackets denote p-values. Wald tests check the null hypothesis that the fracking activities coefficient is greater than the non-fracking activities coefficient. AR(1) is the first-order test for residual autocorrelation. AR(2) is the test for autocorrelation of order 2. Hansen is the test for the overidentification check for the validity of instruments. The number of lags was determined through the Akaike criterion. ***: $p \leq 0.01$; **: $p \leq 0.05$; *: $p \leq 0.10$.

Finally, based on a reviewer's recommendation, we repeat the analysis in Table 4 by explicitly considering whether a nonmetro county is adjacent to a metropolitan area. To this end, we introduce a dummy variable (Dadjacent) that takes the value of 1 if a county is considered as nonmetro and is adjacent to a metro county, and 0 otherwise. The new results are reported in Table 4b and they clearly illustrate first, that the dummy variable is insignificant (potentially implying that the pollution effect does not distinguish between metro and nonmetro areas), while the remaining results are close to those reported in Table 4.

Table 4b

Common correlated effects mean group (CCE-MG) estimates: 1998-2017 (the role of nonmetro counties that are adjacent to metro counties)

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
	Life expectancy	**Mortality Rate**	**Cancer Diseases**	**Cardiac Diseases**	**Respiratory Diseases**
Constant	-0.419**	0.346*	-0.366*	-0.311*	-0.302*
	[0.05]	[0.09]	[0.07]	[0.09]	[0.10]
log(fracking)	-0.038***	0.060***	0.069***	0.066***	0.051***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
log(nonfrack)	-0.012	0.025*	0.015	0.017	0.012
	[0.22]	[0.10]	[0.18]	[0.19]	[0.24]
log(grid)	-0.018*	0.020*	0.023*	0.010	0.011
	[0.10]	[0.09]	[0.08]	[0.24]	[0.23]
log(transport)	0.021*	-0.025*	-0.003	-0.022*	-0.027**
	[0.09]	[0.08]	[0.34]	[0.09]	[0.05]
log(manuf.)	0.040**	-0.034**	-0.023*	-0.026*	-0.035**
	[0.02]	[0.04]	[0.08]	[0.07]	[0.03]
log(income)	0.070***	-0.052***	-0.040***	-0.049***	-0.045***
	[0.00]	[0.00]	[0.01]	[0.00]	[0.00]
D_{met}	-0.044***	0.039***	0.035**	0.037***	0.034**
	[0.00]	[0.01]	[0.03]	[0.01]	[0.03]
Dadjacent	0.014	0.012	0.016	0.011	0.008
	[0.26]	[0.28]	[0.23]	[0.30]	[0.38]
log(age)	-0.042***	0.065***	0.050***	0.048***	0.057***
	[0.01]	[0.00]	[0.00]	[0.00]	[0.00]
log(cigar)	-0.048***	0.054***	0.080***	0.086***	0.094***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
log(race)	-0.039***	0.065***	0.070***	0.059***	0.047***
	[0.01]	[0.00]	[0.00]	[0.00]	[0.00]
un	-0.059***	0.051***	0.065***	0.069***	0.025
	[0.00]	[0.00]	[0.00]	[0.00]	[0.18]
log(bcr)	0.051***	-0.059***	-0.035*	-0.044**	-0.020
	[0.00]	[0.00]	[0.10]	[0.03]	[0.21]
educ	0.081***	-0.068***	-0.075***	-0.093***	-0.059***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]

D2006	-0.078***	0.090***	0.072***	0.079***	0.095***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
DINJ	-0.050***	0.045***	0.074***	0.061***	0.065***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
R^2-adjusted	0.71	0.73	0.77	0.73	0.70
Wald test	[0.01]	[0.01]	[0.01]	[0.02]	[0.02]
County fixed effects	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES

Figures in brackets denote p-values. Wald tests check the null hypothesis that the fracking activities coefficient is greater than the non-fracking activities coefficient. ***: p≤0.01; **: p≤0.05; *: p≤0.10.

6. Conclusion and policy implications

In the early 2000s, the US experienced the beginning of a resource boom after horizontal drilling and hydraulic fracturing technologies were combined in a way that made it economical to extract oil and gas from unconventional geological formations (McNally et al., 218). Given that the US holds large unconventional gas reserves, a large and growing literature has examined the impact of fracking activities on the economic performance and health profile of the population. The expansion of such fracking activities in the US has been controversial so far with no consensus on its health, economic, environmental, and social implications. On one hand, the literature documents that the fracking revolution has caused prices of natural gas to drop by around 47% (Dews, 2015), an 8% increase in personal income, increases in employment by between 500,000 - 600,000 jobs – and each job in the oil and gas sector creates about 2.17 other jobs (Fetzer, 2014), and an increase in the welfare of $48 billion per year for natural gas consumers and producers over the 2007–2013 period (Hausman and Kellogg, 2015). Yet, some strong opposition to fracking has emerged, citing the potential for serious negative impacts on the public health profile due to water contamination and air pollution (Gorski and Schwartz, 2019; Mason et al., 2015). As a result, there are serious concerns among the scientific community that the fracking industry is an uncontrolled health experiment on a colossal scale (Bamberger and Oswald, 2012).

This study examined the effect of fracking operations on the health profile of the population across Oklahoma counties over the period 1998-2017. The findings documented that an increase in the number of (unconventional) wells had a positive impact on mortality rates, and incidences of cancer, cardiac, and respiratory diseases in communities in close spatial proximity, and a negative impact on life expectancy. On average, a 1% increase in the number of fracking wells led to a 4.2% reduction in life expectancy. Similar trends were observed with the remaining health indicators, where a 1% increase in the number of fracking wells led to a 6.8% increase in the mortality rate, a 7.9% increase in cancer diseases, a 7.3% increase in cardiac diseases, and, finally, a 5.9% increase in respiratory diseases. Overall, the empirical results demonstrated a substantial negative impact of fracking operations on the health profile of the population in Oklahoma.

Undoubtedly, pressure has been mounting in recent years on the governments to act as evidence suggests that the local communities are more aware of the negative effects of fracking and they have been registering their opposition to fracking activities across states (Reuters, 2015). However, the response seems to vary across states and, historically speaking, the Oklahoma legislature has always been accused of favouring the oil and gas industry owing to their heavy economic reliance on the latter (see, Yardley, 2016; Mattocks, 2019, among others). For instance, the industry enjoyed automatic immunity from civil suit for the death, injury, and occupational diseases of their workers- a regulation that was ruled unconstitutional only in 2018. Similarly, with the rising frequency of earthquakes since 2009, it was only in 2016 that the Oklahoma Corporation Commission, which acts as the regulator of the oil and gasindustry, asked oil producers to reduce the amount of wastewater they are disposing of the deep underground by 40%, a measure which many critics labelled as “too little, too late” (Yardley, 2016). The state passed laws forbidding local fracking bans in 2015 (Reuters, 2015) and, in the same year, the non-profit public interest organisation, Earthjustice, alleged that legislative measures in Oklahoma focus mainly on chemical disclosure rather than limiting fracking activities (Earthjustice, 2015).

But this is not an issue plaguing only the state of Oklahoma but rather poses a nationwide threat. The negative spillover effects from fracking activities to the health profile of the population have received solid support through county-level standardised incidence ratios for childhood leukaemia across Pennsylvania counties (Fryzek et al., 2013). Fracking practices generate carcinogens through air and water pollution. As a result, exposure to such unconventional activities seems to increase the risk of leukaemia, especially across the children population. Additional supportive evidence is provided by an analysis by the Clean Air Task Force which found that 238 counties across 21 states face cancer risks from oil and gas air toxins generated by unconventional oil and natural gas drilling activities, with the greatest concerns in Texas, Louisiana, North Dakota, Pennsylvania, and Colorado (Fleischman, 2016). Such evidence clearly indicates that a variety of adverse health impacts on every major organ system are being experienced by individuals living near unconventional drilling activities. The experience of such impacted communities clearly attributes declines in health to the presence of UNGD activities and, therefore, formal research like the one reported here is needed to provide solid evidence of the presence of geographical patterns concerning these activities. Based on such evidence, it is recommended that state regulatory agencies take a precautionary approach before allowing further growth of shale developments. In other words, oil and gas firms working in Oklahoma should be better regulated to account for public health damages. Additionally, certain regulatory actions are needed so as these firms can be made to compensate victims for past, recent or upcoming harmful incidences arising from fracking operations. One possibility could be for these oil and gas firms to make payments into a compensation fund for public health victims, such as the Oklahoma Energy Resources Revolving Fund (OERRF) (Konschnik, 2016). Such measures will help in assuring communities a sense of environmental justice; that they and their children will not be subjected to living in an environment contaminated by polluting operations.

Finally, there is a great deal of debate going on about effective regulation, inspection, and enforcement in terms of fracking activities. While the majority of the relevant discussion has been on regulating well construction, less attention has been spent on what goes into the wells and comes out of the wells. Such discussion should be raising significant and as yet unanswered questions about how wells and their related inputs and outputs can be effectively regulated and monitored during production. This discussion is closely associated with the fields of environmental and public health protection, given that some critics have emphasised that the exposure to harmful chemicals due to fracking activities cannot be eliminated through regulation as there are technological and economic limitations to the treatment of emissions into the air, into groundwater, and from waste.

The debate also ignores evidence that geographical distance is the key driver affecting cancerous and non-cancerous health effects in residents near fracking sites. Therefore, policymakers should significantly consider the option that a very safe approach with respect to public health would be to dismiss fracking as a viable option and promote energy technologies that can have less harmful effects on health. Such policies should underpin all rigorous evaluations of what can and cannot be done with regard to assessing the viability and the credibility of effectively regulating, monitoring, and inspecting the fracking industry. In other words, the public health risks results presented in this study can be beyond any effective regulation in which case prevention becomes a major policy option.

Finally, future research could examine (this point was raised by a reviewer) the effects of shifts in the composition of population from migration on measured aggregate health outcomes. It would be interesting to remove the impact of in-migration on health outcomes following the resource curse literature in assessing the effects of fracking in education attainment (Rickman et al., 2017). However, our focus in this analysis is on the impact of UNGD on the health profile of the population across 76 Oklahoma counties, and data constraints do not allow us to control for effects of shifts in the composition of population from migration on measured health outcomes.

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