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Title:
Costs of increasing oil and gas setbacks are initially modest but rise sharply*

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ABSTRACT
Spatial setback rules are a common form of oil and gas regulation worldwide - they require minimum distances between oil and gas operations and homes and other sensitive locations. While setbacks can reduce exposure to potential harms associated with oil and gas production, they can also cause substantial quantities of oil and gas resources to be unavailable for extraction. Using both theoretical modeling and spatial analysis with GIS tools on publicly available data, we determine oil and gas resource loss under different setback distances, focusing on Colorado counties as a case study. We show that increasing setbacks results in small resource loss for setbacks up to 1500 feet, but resource loss quickly increases with longer setbacks. Approximately $5 billion in annual resource revenues would be lost in Colorado under 2500-foot setbacks, a distance recently proposed in Colorado Proposition 112 and California AB 345.

JEL **classifications: Q48, Q53, Q58.**
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Introduction

Advances in oil and gas extraction techniques have led to a boom in production from "unconventional" hydrocarbon sources in the US and abroad[1,2]. While this resource boom has created benefits, it has also generated controversy and concern regarding local health, water quality, and related property value impacts[3-13]. Within the US, many states regulate oil and gas operations with setbacks that require wells to be sited on the order of 200-1000 feet from buildings and other sensitive locations. In jurisdictions such as Colorado, Alberta, and New South Wales, these setback regulations have been motivated by concerns about exposure to harmful industrial accidents, air pollution, noise, and other hazards and nuisances[14]. An important feature of modern oil and gas extraction is that horizontal wells can run laterally for miles underground[15]. As such, oil and gas companies can feasibly access resources underneath surface setback areas, provided there are sufficient "islands" of available surface area to drill from. Increasing setback distances would have minimal impacts on resource availability while these "islands" exist. However, as the setbacks from different sensitive sites overlap, these drillable islands disappear, along with the access to subsurface resources and the economic value associated with them.

To date, there is no literature quantifying the costs of setbacks. A large literature indirectly quantifies the benefits of setbacks, which largely stem from reductions in human exposure to environmental harms related to oil production. While there are multiple exposure pathways and substantial uncertainties regarding the exact spatial scale and magnitude of these environmental harms, negative effects of proximity to unconventional oil and gas wells on human health, noise, air quality, and home values have been documented[3-13]. Epidemiologic studies have found evidence of negative human health outcomes at a regional scale[12].

To assess the costs of increasing setbacks, we employ two approaches. First, we develop a geometric model to derive an analytical relationship between available subsurface resources and setback distances as a function of housing density. Second, we use GIS spatial analysis tools to empirically analyze the impacts of setback distances on resource unavailability for our case study of counties in the state of Colorado. Using publicly available data, we calculate the inaccessible surface and subsurface area and foregone resource revenue for each county under different setback distances and assumptions regarding horizontal drilling. Both approaches demonstrate that i) the costs of setbacks up to roughly 1500 feet are modest, provided firms can drill horizontally, and ii) costs rapidly increase as setbacks are increased from 1500 feet to 2500 feet, resulting in a nearly order-of-magnitude increase in resource unavailability and consequently an additional $4.3 billion in foregone annual resource revenues for Colorado. This dramatic increase in costs illuminates the need for further understanding of the spatial benefits and costs of setback policies in order to balance health concerns against resource extraction concerns when setting setback distances.

Data and methods

Within the US, many states regulate oil and gas operations with setbacks that typically vary between 200-1000 feet, as shown in Table 1[16-18]. The specific statutory language may vary, but typically they require minimum distances between oil and gas operations and occupied dwellings, schools, water sources, ecologically vulnerable areas, and other sensitive locations.

We choose Colorado as a study setting for several reasons. First, Colorado has a rich conventional and unconventional oil and gas history in several regions across the state, and is the 5th largest oil-producing state and 8th largest gas-producing state as of April 2019[19,20]. Second, the distribution of housing density in Colorado counties is similar to other oil and gas producing states. Specifically, the 10th and 90th percentile of housing density by county in Colorado is 1 and 127 houses per square mile, compared to 1.3 and 158.1 houses per square mile for twelve other major oil and gas producing states[19-21]. Third, setbacks have particular salience in Colorado in the wake of a recent ballot referendum on increasing setback distances from 500 feet to 2500 feet[22] (see Supporting Information).

Figure 1 presents three maps of wells in Colorado, with Figure 1a displaying statewide oil and gas wells, as well as county boundaries. Wells are spread broadly across the state, and there is substantial inter-county variation in well density. Figure 1b zooms in to the northern Front Range, the most populated region of the state. This map shows municipalities in yellow, ranging from the northern Denver suburbs to Fort Collins (top left) and Greeley (upper right), where there is dramatic overlap between the municipalities and oil and gas wells. Figure 1b outlines Greeley, Colorado, which appears to have relatively little oil and gas activity. Figure 1c zooms in on Greeley and shows only horizontal wells. Note that while there are relatively few wellheads in the municipal boundary of Greeley, much of Greeley is underlain by horizontal wells.

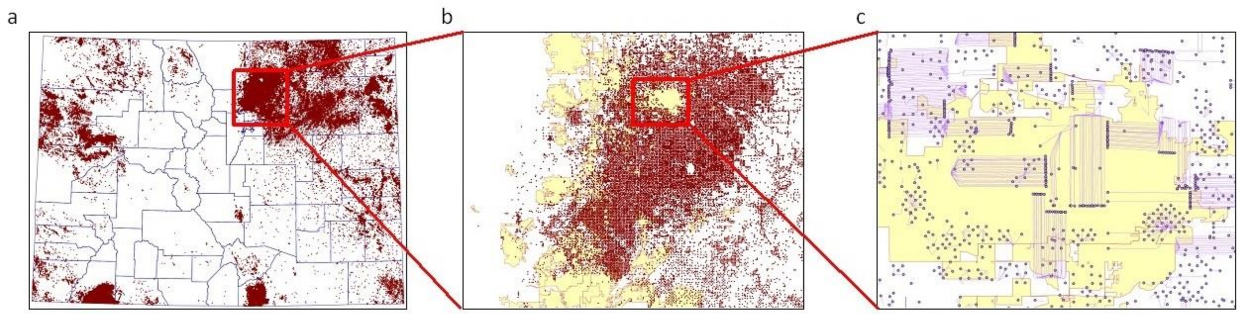

Figure 1: Map showing O&G operations and population in CO. (a) shows all wells in Colorado (red dots) with county borders (blue lines). (a) is approximately 380 mi by 280 mi. (b) zooms in to the northern Front Range, ranging from Denver suburbs to Fort Collins and Greeley. Municipalities are in yellow. (b) is approximately 60 x 50 mi. (c) zooms in to Greeley, Colorado and shows horizontal wellbores (purple lines). (c) is approximately 10 mi by 8 mi.

We utilize several publicly available data sources for our GIS analysis. First, the Microsoft US Building Footprints Project is a comprehensive dataset of building footprints for the US, of which we use the 2,080,808 buildings in Colorado[23]. Second, the U.S. Geological Survey maintains high resolution hydrological data of all U.S. states and territories, specifically water bodies, water areas, and water flows, which we augment with wetland data provided by the U.S. Fish and Wildlife Service[24,25]. Next, the USGS also provides shapefiles of federal land, including disaggregation by agency such as the Bureau of Land Management (BLM)[26]. Finally, county shapefiles and other county-specific data are maintained by the Census Bureau[21,27].

Geometric analysis methodology

The purpose of the geometric analysis is to develop intuition for how setbacks affect resource availability and provide some guidance in terms of the setback distances at which resource availability may be strongly impacted. As an illustrative example (Fig 2), consider evenly spaced houses a half mile apart on a square grid, implying houses are 2640 feet apart (corresponding to a typical density of four houses per square mile for our study region[21]). Each set of four houses creates a square, where the center of each square is the area that is the farthest distance away from any house. Using the Pythagorean Theorem, the distance x between any house and the center of the square is

$$x^2 + x^2 = 2640^2 \rightarrow x = 2640 * \left(\sqrt{2}/2\right) \approx 1867 \text{ feet}$$

(1)

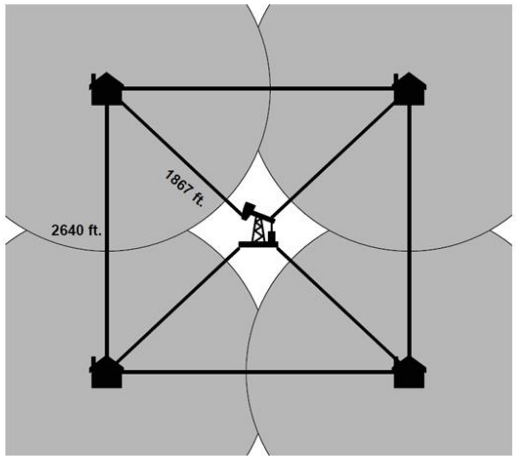

Figure 2: Setback geometry intuition - This figure illustrates conceptual framework for evenly spaced houses on a square grid with a housing density of 4 houses per square mile. Grey areas represent surface area that is inaccessible to drilling due to setbacks.

As the setback distance r increases, more surface area becomes inaccessible. However, as long as the center of the square remains open, that is provided $r < 1867$ feet, the entirety of the subsurface can still be reached via horizontal drilling. Beyond that point, when $r \geq 1867$, both the surface and subsurface will become inaccessible.

The above can be generalized to different levels of housing density while maintaining the uniform, square grid spacing assumption. If n represents the housing density (houses per square mile), inaccessible surface area is given by:

$$\begin{cases} n\pi(\frac{r}{5280})^2 & r \leq 5280/2\sqrt{n} \\ n\pi(\frac{r}{5280})^2 - 2nA \quad if & 5280/2\sqrt{n} < r < 5280/\sqrt{2n} \\ 1 & r \geq 5280/\sqrt{2n} \end{cases}$$

(2)

where A is the area of the lens created by the overlapping setback circles and is given by:

$$A = \pi(\frac{r}{5280})^2 - 2(\frac{r}{5280})^2 \tan^{-1}\left(\frac{\frac{1}{\sqrt{n}}}{\sqrt{4\left(\frac{r}{5280}\right)^2 - \left(\frac{1}{\sqrt{n}}^2\right)}}\right) - \frac{1}{2\sqrt{n}}\sqrt{4\left(\frac{r}{5280}\right)^2 - \left(\frac{1}{\sqrt{n}}\right)^2}$$

(3)

GIS methodology

We use GIS spatial analysis tools to calculate the subsurface resource unavailability at given setback distances, under different assumptions regarding horizontal drilling distances. To do this, we follow a four-step process, which could be readily applied to other states or regions and/or modified to incorporate alternative assumptions. In step one, we download and project the data as described in the previous section. In step two, in order to determine the surface that is off-limits to drilling, we create buffer zones around vulnerable areas—buildings and waterways—for each of 64 counties in Colorado for a range of setback distances. We analyze setbacks between 250-3500 feet, at 250-foot increments.

In step three, we determine the surface area available for drilling. We take the difference between the county area and the area off-limits to drilling for each setback distance. Because oil and gas drilling on federal lands is regulated federally, federal lands are removed from the calculations of total area and total surface area available for drilling. To account for the fact that oil and gas operations require space to set up operations, we also assume that any area with less than 10 acres of available surface area is unavailable for drilling.

In step four, we determine the subsurface area available for drilling. We create buffer zones around the surface areas available for drilling for various horizontal drilling distances. Drilling across county boundaries is accounted for, as discussed below. We modeled horizontal drilling distances between 1-3 miles, at integer mile intervals. We use two-mile laterals as our default distance[28,29], with one-mile and three-mile laterals as robustness checks (see Supporting Information).

Because state regulations do not apply to federal lands, we do not include resources under federal lands in the calculation of total area or the calculation of subsurface area available for drilling. However, drilling from federal lands into state lands is allowed, and so the position of federal lands can affect available subsurface area. That is, in principle it is possible for a well located on federal lands, which is not subject to state regulations such as setbacks, to access mineral leases located under state-regulated land. Drilling is prohibited on many types of federal lands, such as national parks and wilderness areas, and impractical on others such as many national forests, and as such we assume that no horizontal drilling out of those types of federal lands can take place, consistent with observed patterns of oil and gas operations in the state. However, there are existing oil and gas operations located on federal BLM land in Colorado, and therefore we assume BLM land is available for drilling horizontally into neighboring state-regulated lands.

We account for cross-county extraction activities by allowing for setbacks around vulnerable areas in one county in Colorado to extend into adjacent counties. That is, we incorporate land and vulnerable areas around the county within the maximum setback distance plus the maximum lateral drilling distance to determine available surface and subsurface area. This captures the possibility of vulnerable areas outside the county affecting available land inside the county, and the possibility of wells located outside the county drilling into the county. We then subset the land within the county to determine the surface and subsurface area accessible to oil and gas drilling.

We do not account for the potential to drill horizontally from other states into Colorado. Because the maximum setback distances considered in our analysis is less than a mile, the percent of land in Colorado which could become off limits due to buildings and waterways in adjacent states is minimal. Because the maximum lateral drilling distance considered is three miles, drilling operations in adjacent states will also have a minimal impact on subsurface availability.

Data details

We compile data on county shapes, federal lands, and buildings and waterways where setback rules may apply. We use much of the same data as in a setback analysis of surface area conducted by the Colorado Oil and Gas Conservation Commission[30], which analyzed the effects of Proposition 112, 2500-foot setbacks, on available surface area (but not subsurface area) for drilling activities in Colorado. Our data differs from the COGCC study in that we use a more complete building dataset and we disaggregate federal land into its various components (e.g. BLM versus National Forest). The included R code will download and compile all relevant data files required for the analysis and provide information on how to conduct a similar analysis for other states.

The county shapefiles maintained by the Census Bureau provide the boundaries for each of the 64 Colorado counties, which is our unit of analysis. Setback laws are applied at the state or local level, implying different rules will hold for federal land. We use both federal land shapefiles and the subset of federal land owned by the Bureau of Land Management (BLM), as most oil and gas drilling on federal lands occurs on BLM land. As noted above, oil and gas setback regulations apply to buildings and to vulnerable areas such as waterways. We use building shapefiles from the Microsoft US Building Footprints project, which uses satellite data combined with machine learning to construct computer-generated building footprints and contains footprint data for more than 100 million buildings. We utilize the Colorado dataset, which includes 2,080,808 buildings. The USGS maintains high resolution hydrological data of all U.S. states and territories, and is separated into three separate files, namely: water bodies, water areas and water flows. We aggregate these three files into a single hydrology data set, and then augment the hydrology dataset with wetland data provided by the U.S. Fish and Wildlife Service.

Each data set is projected using a Universal Transversal Mercator (UTM) projection, with the UTM zone set at 13 for Colorado. This ensures all data sets use the same coordinate system and can be integrated. The UTM projection further allows distances to be easily calculated.

Variation across state setback policies

A complicating feature of studying oil and gas setbacks is that US states have setbacks that vary along at least four different dimensions i) distance, ii) features, iii) measurement, and iv) specificity[16-18]. As noted above, US state setback distances are typically on the order of 200-1000 feet, though some states allow local counties or municipalities to place setbacks at longer distances[31]. While that range may seem somewhat narrow, the 1000-foot setback in Maryland places 25 times as much surface area off-limits as the 200-foot setback in Ohio. In addition to the variation in distance, state setback rules also vary tremendously in terms of what features (e.g. houses, schools, churches, roads, waterways) they apply to. In a 2013 review of state statutes[16], buildings and water sources were the most common features associated with setbacks, with 21 of 31 states examined having setback rules covering buildings and 13 of 31 states having setback rules covering water sources. The manner in which setback distances are measured also varies, with most states measuring from the well-bore, though some states such as Pennsylvania specify alternative measurement distances from the pad[16]. Finally, further complicating analysis is that setback rules also vary in their specificity, with Wyoming's setbacks applying to "where people are known to congregate" versus West Virginia's setbacks from a "building 2500 sq. ft. or larger used to house or shelter dairy cattle or poultry husbandry" or a "naturally reproducing trout stream"[17].

Given the heterogeneity above, we need to make some assumptions regarding which features to model. Given the recent ballot measure in Colorado, and the fact that its existing setback rules were reasonably representative, Colorado is a useful case study to base our analysis on. In terms of the specific ballot language[32], *Proposition 112: Increased Setback Requirement for Oil and Natural Gas Development* posed to voters the following question: "Shall there be a change to the Colorado Revised Statutes concerning a statewide minimum distance requirement for new oil and gas development, and, in connection therewith, changing existing distance requirements to require that any new oil and gas development be located at least 2,500 feet from any structure intended for human occupancy and any other area designated by the measure, the state, or a local government and authorizing the state or a local government to increase the minimum distance requirement?" The accompanying Colorado 2018 State Ballot Information Booklet[43] further clarified that "structures" includes buildings where people live or work and that “any other area” includes certain vulnerable areas such as recreation areas and water sources including lakes, rivers, and streams (see Supporting Information for full text of proposed statute revision).

GIS analysis caveats

There are important caveats to our GIS analysis. Several apply to the question of calculating the spatial effect of the setback. As noted above, existing regulations typically apply to occupied structures – that is, buildings with occupancy permits. We use Microsoft’s building footprint data, which likely does not perfectly correspond to occupied structure footprints. For example, barns and other large outbuildings would be captured in the Microsoft data, but would not count as an “occupied structure” under state statutes. We assume that BLM land is the only type of federal lands that are available for drilling. While most federal land in Colorado is administered by the US Forest Service or BLM, each of which allow extractive use, other lands are national parks, military bases, reservoirs, and other uses on which drilling is unlikely or prohibited. We do assume that an accessible surface patch must be at least 10 acres to be drillable in order to account for surface logistical needs (truck traffic, drilling rig, etc). However, we impose no constraints on the shape of this 10-acre patch, so in principle a 10-acre sliver of land would qualify. We also assume that firms can drill horizontally in any direction (i.e. circular drilling), but this is not geologically feasible in all areas.

Additional caveats apply to whether or not our analysis answers relevant policy questions. First, setback rules vary from state to state and future possible setback rules are unknown. Setbacks might apply only to wells or also apply to other surface logistics such as storage tanks or compressor stations, for example. We omit considerations of within-county spatial variation in subsurface quality, when in practice some areas have resource endowments that are denser or more technologically feasible than others. Even if subsurface resources are accessible under increased setbacks, firms may face increased costs such as increased drilling distances, or increased costs of building roads to drill sites. Finally, we use contemporary maps of buildings. Population growth will set new surface areas off limits and may increase the inaccessible subsurface area.

Results and Discussion

Geometric analysis results

The entirety of the subsurface resource is accessible up to 1867 feet, and inaccessible beyond that, in our geometrical model with horizontal drilling and four evenly spaced houses per square mile (Figure 3). Without horizontal drilling, resource unavailability increases with the area of the four setback circles until the setback circles intersect (at 1320 feet). Beyond that, resource unavailability rises more slowly as the setbacks create overlapping lenses, and then at setbacks of 1867 feet, the circles fully envelope the surface area and 100% of the resource is unavailable.

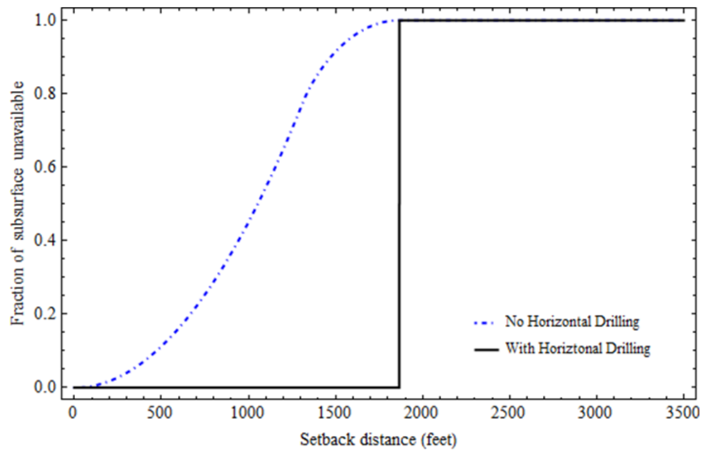

Figure 3: Fraction of inaccessible subsurface area from geometric analysis. This calculates the fraction of unavailable subsurface resources with no horizontal drilling (blue dashed) and with horizontal drilling (black solid) assuming a housing density of 4 houses per square mile.

Intuitively, as long as the setback distance is less than 1867 feet, there will be an "island" of accessible surface area between homes, and horizontal drilling can access the entirety of the subsurface resource. However, if setback distances exceed 1867 feet, there will be no surface area accessible to drill wells, and the subsurface resource will be completely unavailable. This can be generalized to any housing density per square mile, n, such that the equivalent "step" in Figure 3 will occur at $\frac{5280}{\sqrt{2n}}$ feet, whereby quadrupling the housing density halves the distance at which the step in Figure 3 occurs. Up to that point, horizontal drilling technologies imply that the costs of increasing setbacks are minimal. Beyond that point, geometry dictates that the costs skyrocket.

In reality of course, the relationship between subsurface resource availability and setback distance for Colorado counties will not be a perfect step function as housing density and spacing will vary across and within regions. Wetlands, other hydrological features, and federal lands not subject to state regulations further complicate the relationship between setback distances and resource availability. Nonetheless, the geometric thought experiment provides intuition regarding the distances at which setbacks may start to impact resource availability. For example, the median housing density for Colorado counties is 6.5 housing units per square mile[21], which (if uniform) would imply resource unavailability at just shy of 1500-foot setbacks.

GIS analysis results

Resource losses from setbacks are small for moderate setback distances (up to approximately 1500 feet), but increase rapidly beyond that for our case study of Colorado counties, consistent with the geometric analysis. Resource unavailability increases by an order of magnitude if setbacks are increased from 1500 feet to 2500 feet. Figure 4 illustrates the impacts of 1500-foot setbacks for Weld County. Given the houses (black dots) and waterways (blue shapes) in Figure 4a, the surface areas that are off-limits to drilling due to the 1500-foot setbacks are shown in grey in Figure 4b. Taken the inverse of that area and removing federal lands reveals the available surface area that can be drilled shown in green in Figure 4c. Without horizontal drilling, this implies that only 26.3% of the subsurface resource would be accessible in Weld with a 1500-foot setback. By contrast, with horizontal drilling of two-mile laterals, Figure 4d shows that a substantially larger fraction of the subsurface resource, 98.5%, can be accessed. With typical two-mile laterals[28,29] the only inaccessible resources would be located in Greeley and the other population centers in the southwest corner of the county. The above findings are consistent with the geometric analysis in that horizontal drilling allows access to subsurface resources as setback distances increase, up to a point.

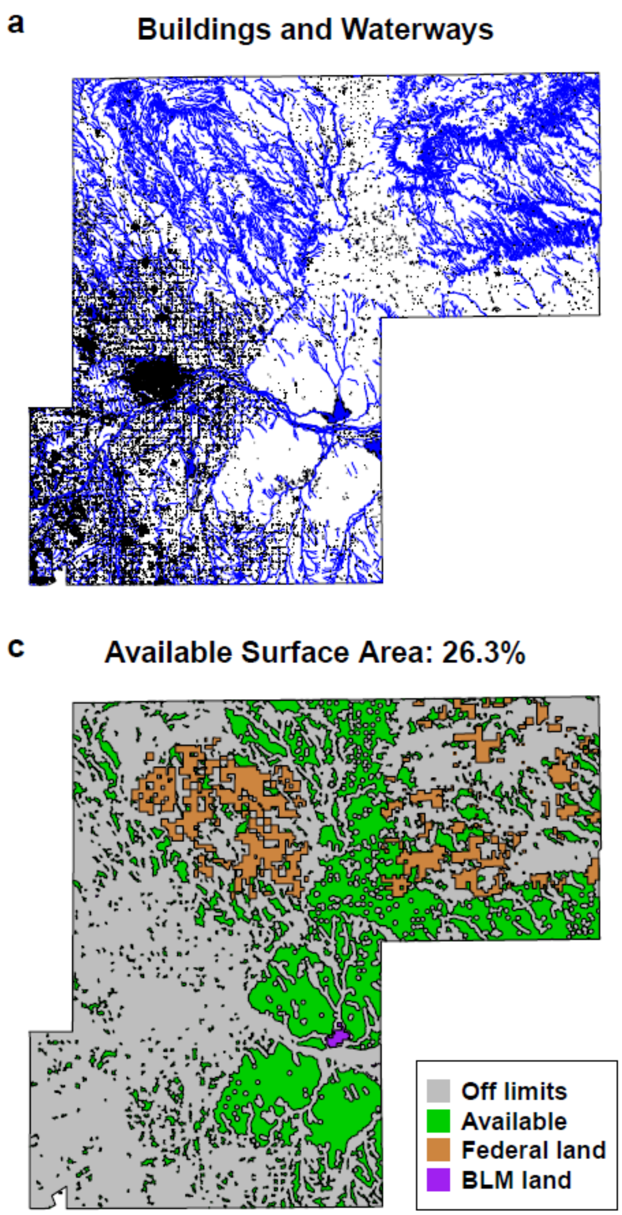

Figure 4: GIS analysis - four step process to determine accessible surface and subsurface area for Weld County, Colorado, with 1500-foot setback and 2-mile horizontal drilling. (a) Buildings (black) and waterways (blue) represent the entities that the setback regulation applies towards. (b) Calculated setback areas (grey) from buildings and waterways (1500 foot setback). (c) Surface area accessible (green) for drilling (inverse of (b)), along with federal lands in orange and BLM lands in purple. (d) Accessible subsurface area (green) given 2-mile horizontal drilling. .

Applying the same analysis to all 64 counties in Colorado and assuming two-mile horizontal drilling, Figure 5 illustrates that while the costs of increasing setbacks are initially modest (up to around 1500 feet), they swiftly rise beyond that (see Supporting Information for similar figures for one-mile and three-mile laterals). For example, 92% of counties have less than 15% resource unavailability at setbacks of 1250 feet, and even with 1500-foot setbacks, the median resource unavailability across counties is only 3%. However, further increasing setbacks to 2500 feet results in a nearly order-of-magnitude increase in median resource unavailability, and roughly a third of counties have at least 40% of their resources unavailable at that distance. At 3500 feet, even low population density counties with a single house per square mile would have 20% of their subsurface unavailable. The geometric analysis again provides intuition for the above results, as larger setback distances begin to squeeze out drillable surface areas and costs swiftly rise beyond roughly 1500-foot setbacks.

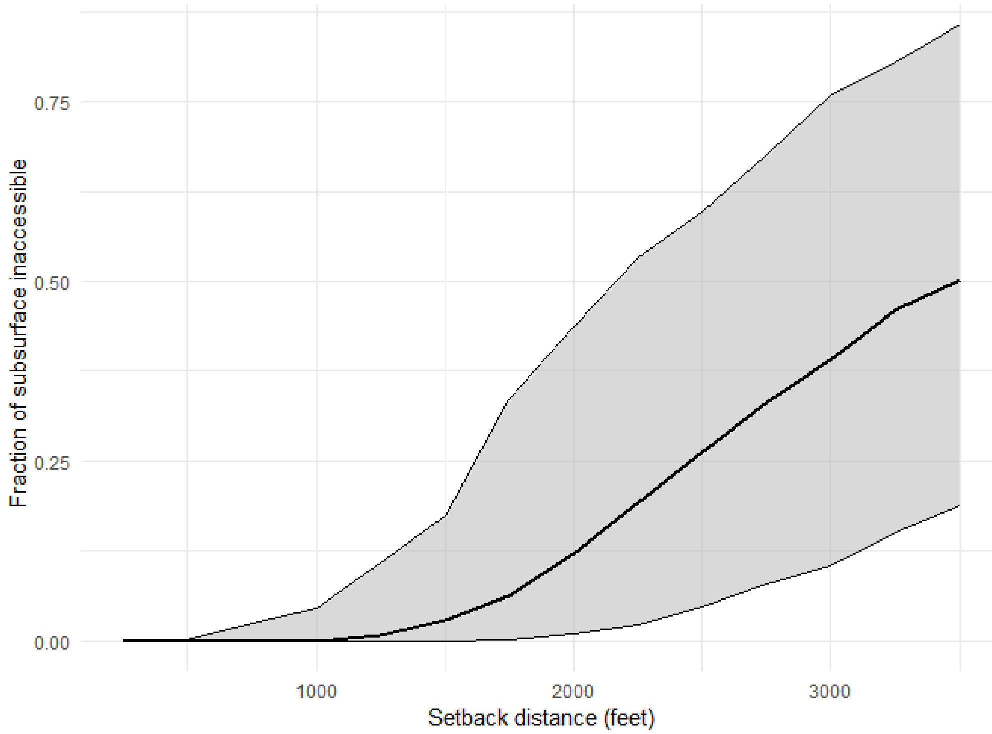

Figure 5: Fraction of inaccessible subsurface area in Colorado counties based on GIS analysis. Calculation assumes two-mile horizontal drilling. Thick solid line represents median of 64 Colorado counties. Gray area illustrates 10th-90th percentile range

This sharp increase in resource unavailability has significant economic implications. We calculate the impact of setback distances on oil and gas total revenue – the quantity of lost production times the prices of oil and gas. For each county, multiplying 2018 oil and gas production by 2018 average prices of oil and gas – $65.23 per barrel (West Texas Intermediate) and $3.15 per mmbtu (Henry Hub)[33-35] – gives the total oil and gas revenue per county. Multiplying by the fraction of inaccessible subsurface area for each setback distance and county from the GIS analysis yields the resource revenue lost for each county by setback distance. Aggregating statewide, with a 2500 foot setback the total resource revenue loss is $97 billion in net present value (assuming a 5% discount rate), or nearly $5 billion per year, which is approximately 1.5% of Colorado's Gross State Product[36]. By contrast, the statewide annual resource revenue loss under 1500 foot setbacks would be roughly $500 million. At the county level, the average county would lose $105 per person per year in oil and gas revenue under a 1500-foot setback, increasing to $663 per person per year under a 2500-foot setback. This is right-skewed and dominated by counties with very large production or very low populations. Weld County, a major oil and gas producer, would lose $665 per person per year in revenue under a 1500-foot setback and $13,005 per person per year under a 2500-foot setback, but fewer than 15% of counties have above-average losses. Alternative horizontal drilling assumptions (1 mile or 3 mile) yield similar order-of-magnitude resource revenue losses (see Supporting Information). Thus, while the ability to drill horizontally can initially mitigate the costs of increased setbacks, this is true only up to the point that overlapping setbacks begin to quickly eliminate the surface areas needed for drilling access.

Policy implications and discussion

Policy debates regarding setbacks and related oil and gas regulations have primarily occurred at the state and local level, where proponents of increased setback distances have highlighted health benefits, while opponents point to the rising costs of resource unavailability and associated loss of high-paying jobs and tax revenues[31,37-40]. This conflict between human health impacts and resource extraction came to a head in a 2018 Colorado state referendum, where a ballot initiative (Proposition 112 – see Supporting Information) to increase setbacks from 500 feet to 2500 feet was defeated 45-55[22]. The election featured $40 million in industry spending that focused heavily on the potential loss of access to oil and gas resources and attendant consequences for employment, tax revenue, and other fiscal impacts[22]. Both supporters and opponents widely characterized the proposition as a “ban” on drilling. Assembly Bill AB 345 currently in the legislative process in California similarly mandates 2500-foot setbacks, with similar arguments for and against the legislation[41].

The health benefits of increased setbacks are an area of ongoing research[3-13], and given the uncertainties involved, it is difficult to provide a precise statement regarding an “optimal” setback distance that balances health and related concerns against resource losses. Nonetheless, our analysis of the costs of increased setbacks clarifies part of the balancing act and provides some preliminary guidance. In short, because increasing setbacks results in minimal resource loss initially, (approximately $0.5 billion annually at 1500 feet), relatively modest public health benefits would likely justify setbacks that are larger than current distances of around 500 feet. However, because of the rapid increase in costs as setbacks are increased (nearly $5 billion annually at 2500 feet, roughly 1.5% of Colorado’s Gross State Product), the health benefits would have to be substantial to justify setbacks as large as the recent policy proposals of 2500 feet in Colorado (Prop 112) and California (AB 345). Clearly, additional research on the spatial dimensions of impacts from oil and gas operations (e.g. emissions from fracking techniques, atmospheric transport modelling, and health effects of exposure) would help to further refine optimal setback distances.

Given recent policy activity in Colorado and California, additional guidance regarding the benefits and costs of oil and gas setbacks is crucial. We focus on Colorado as a case study into the resource extraction costs of setbacks, as it is a state with active production that has similar characteristics to many other oil and gas producing states across the US. Analysis of select, important oil and gas counties in other states reveals similar patterns to those above (See Supporting Information). More generally across the globe, even if setbacks are not explicitly mandated, oil and gas producing regions still balance health and other costs of resource extraction against benefits from employment, tax revenues, and other fiscal considerations. Similarly, other energy resources such as nuclear and wind power may be subject to spatial setback rules[14,42] that balance health and safety concerns against the benefits of energy production. Particularly for the rapidly growing wind industry[43], spatial siting issues for wind turbines and farms are likely to become increasingly important[44].

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Author contributions

SE, DK, and PM conceived the research. SE developed the R code to conduct the GIS analysis. DK executed the geometric analysis. PM executed the economic analysis. All authors contributed significantly to writing. Order of authors follows the convention in economics whereby alphabetical ordering indicates equal authorship.

Competing Interests

The authors declare no competing financial or non-financial interests.

Data Availability

The data that support all the empirical findings in this study are based on publicly-available data as referenced herein. The R code used to download the spatial data and run the analysis are available from [https://github.com/sericson0/Well_Setbacks]. These data can also be obtained from the corresponding author upon request.

Tables

Table 1: Setback distances to buildings across U.S. states

State	Distance (ft)	State	Distance (ft)
Alabama	200	Michigan	300
Arkansas	100	New Mexico	*
Arizona	150	New York	100
California	*	North Carolina	650
Colorado	500	North Dakota	500
Georgia	330	Ohio	200
Idaho	300	Pennsylvania	500
Illinois	500	Tennessee	200
Indiana	200	Texas	200*
Kentucky	150	Virginia	200
Louisiana	500	West Virginia	625
Maryland	1000	Wyoming	350

State setbacks to buildings, based on reviews of state statutes[14-16]. See text for additional discussion of variation across states in terms of setback policies.
* indicates setback policies administered at the local (county, municipality) level.

Additional Information

Proposition 112 text

Full text of the Colorado Proposition 112 Increased Setback Requirement for Oil and Natural Gas Development ballot measure from the 2018 election[1]:

Be it Enacted by the People of the State of Colorado:

SECTION 1. In Colorado Revised Statutes, **add** 34-60-131 as follows:

34-60-131. Mitigation of adverse oil and gas impacts to health and safety – buffer zones – legislative declaration - definitions. (1) THE PEOPLE OF THE STATE OF COLORADO FIND AND DECLARE THAT:

(a) PROXIMITY TO OIL AND GAS DEVELOPMENT, INCLUDING THE USE OF HYDRAULIC FRACTURING, HAS DETRIMENTAL IMPACTS ON PUBLIC HEALTH, SAFETY, WELFARE, AND THE ENVIRONMENT;

(b) SUCH IMPACTS ARE REDUCED BY LOCATING OIL AND GAS OPERATIONS AWAY FROM OCCUPIED STRUCTURES AND VULNERABLE AREAS; AND

(c) TO PRESERVE PUBLIC HEALTH, SAFETY, WELFARE, AND THE ENVIRONMENT, THE PEOPLE DESIRE TO ESTABLISH A BUFFER ZONE REQUIRING ALL NEW OIL AND GAS DEVELOPMENT IN THE STATE OF COLORADO TO BE LOCATED AN INCREASED DISTANCE AWAY FROM OCCUPIED STRUCTURES, INCLUDING HOMES, SCHOOLS AND HOSPITALS,AS WELL AS VULNERABLE AREAS.

(2) AS USED IN THIS SECTION, UNLESS THE CONTEXT OTHERWISE REQUIRES:

(a) "OCCUPIED STRUCTURE" MEANS ANY BUILDING OR STRUCTURE THAT REQUIRES A CERTIFICATE OF OCCUPANCY OR BUILDING OR STRUCTURE INTENDED FOR HUMAN OCCUPANCY, INCLUDING HOMES, SCHOOLS, AND HOSPITALS.

(b) "OIL AND GAS DEVELOPMENT" MEANS EXPLORATION FOR, AND DRILLING, PRODUCTION, AND PROCESSING OF, OIL, GAS, OR OTHER GASEOUS AND LIQUID HYDROCARBONS, AND FLOWLINES AND THE TREATMENT OF WASTE ASSOCIATED WITH SUCH EXPLORATION, DRILLING, PRODUCTION AND PROCESSING. "OIL AND GAS DEVELOPMENT" INCLUDES HYDRAULIC FRACTURING.

(c) "VULNERABLE AREAS" MEANS PLAYGROUNDS, PERMANENT SPORTS FIELDS, AMPHITHEATERS, PUBLIC PARKS, PUBLIC OPEN SPACE, PUBLIC AND COMMUNITY DRINKING WATER SOURCES, IRRIGATION CANALS, RESERVOIRS, LAKES, RIVERS, PERENNIAL OR INTERMITTENT STREAMS, AND CREEKS, AND ANY ADDITIONAL VULNERABLE AREAS DESIGNATED BY THE STATE OR A LOCAL GOVERNMENT.

(d) "LOCAL GOVERNMENT" MEANS ANY STATUTORY OR HOME RULE COUNTY, CITY AND COUNTY, CITY, OR TOWN LOCATED IN THE STATE OF COLORADO.

(3) THE PEOPLE OF THE STATE OF COLORADO HEREBY ESTABLISH THAT ALL NEW OIL AND GAS DEVELOPMENT NOT ON FEDERAL LAND MUST BE LOCATED AT LEAST TWO THOUSAND FIVE HUNDRED FEET FROM AN OCCUPIED STRUCTURE OR VULNERABLE AREA. FOR PURPOSES OF THIS SECTION, THE REENTRY OF AN OIL OR GAS WELL PREVIOUSLY PLUGGED OR ABANDONED IS CONSIDERED NEW OIL AND GAS DEVELOPMENT.

(4) THE STATE OR A LOCAL GOVERNMENT MAY REQUIRE THAT NEW OIL AND GAS DEVELOPMENT BE LOCATED A LARGER DISTANCE AWAY FROM OCCUPIED STRUCTURES OR VULNERABLE AREAS THAN REQUIRED BY SUBSECTION (3) OF THIS SECTION. IN THE EVENT THAT TWO OR MORE LOCAL GOVERNMENTS WITH JURISDICTION OVER THE SAME GEOGRAPHIC AREA ESTABLISH DIFFERENT BUFFER ZONE DISTANCES, THE LARGER BUFFER ZONE GOVERNS.

(5) THIS SECTION TAKES EFFECT UPON OFFICIAL DECLARATION OF THE GOVERNOR AND IS SELF-EXECUTING.

(6) THIS SECTION APPLIES TO OIL AND GAS DEVELOPMENT PERMITTED ON OR AFTER THE EFFECTIVE DATE.

Additional analyses

Here we describe several analyses which complement our core results. We explore both different assumptions about horizontal drilling distances and different study sites. Our results are broadly similar to the paper's main results.

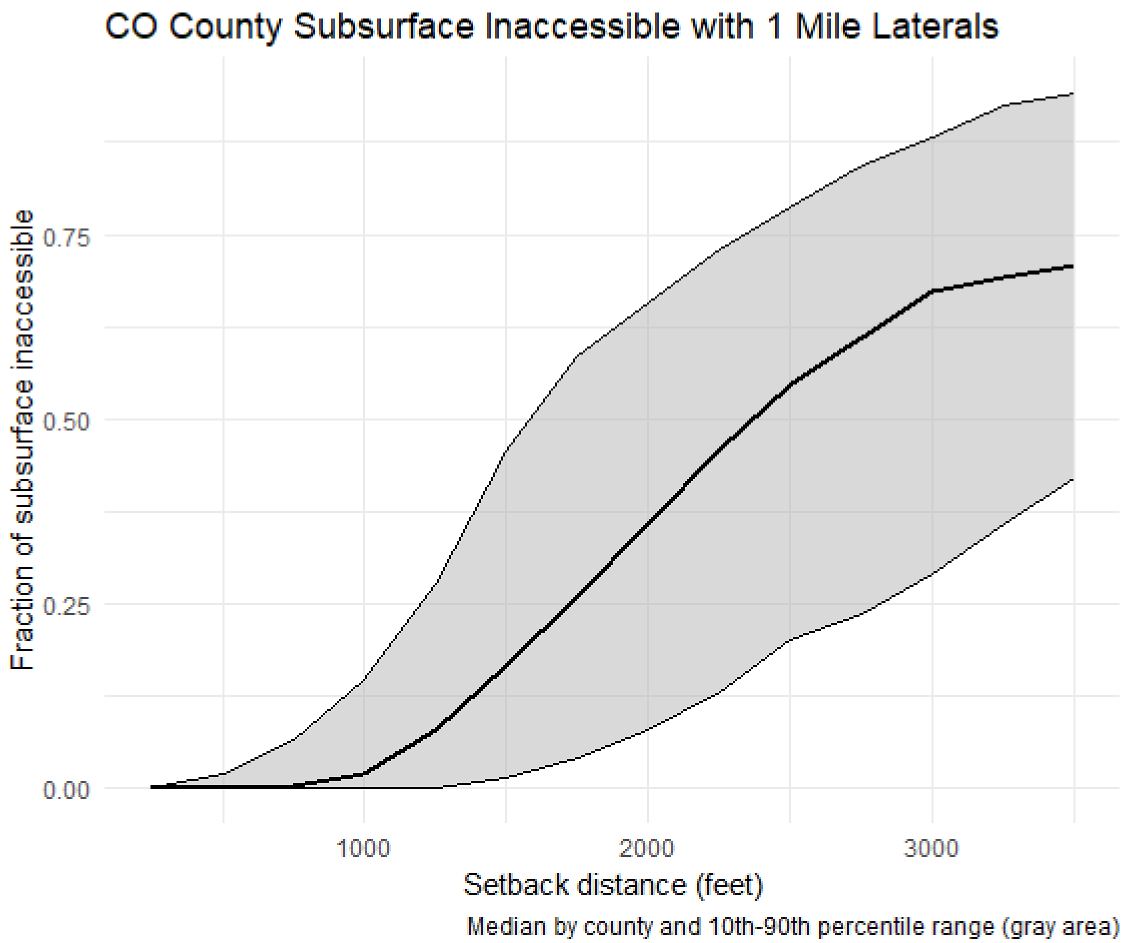
First we explore sensitivity to horizontal drilling distance. While two miles is a typical distance for a horizontal lateral, drilling that distance is not feasible in all areas. Conversely, the longest laterals are substantially longer than two miles. In Supporting Figures S1 and S2, we repeat our core analysis but assume that firms can drill horizontally for 1 and 3 miles, respectively. These figures are qualitatively similar to Figure 5. We see that the unavailability curve shifts left with shorter laterals and right with longer laterals, but in each case there is a pronounced S-curve with minimal resource unavailability for setbacks of up to 1000-1250 feet, but rapidly increasing resource unavailability for further setbacks beyond 1500 feet.

Implications for foregone total resource revenues are similar to the two mile case. With 1 mile horizontal drilling, a net present value of $48 billion in total resource revenue would be lost with 1500 foot setbacks, increasing to $168 billion with 2500 foot setbacks. With 3 mile horizontal drilling, a net present value of $3.5 billion would be lost with 1500 foot setbacks, compared to $67 billion with 2500 foot setbacks.

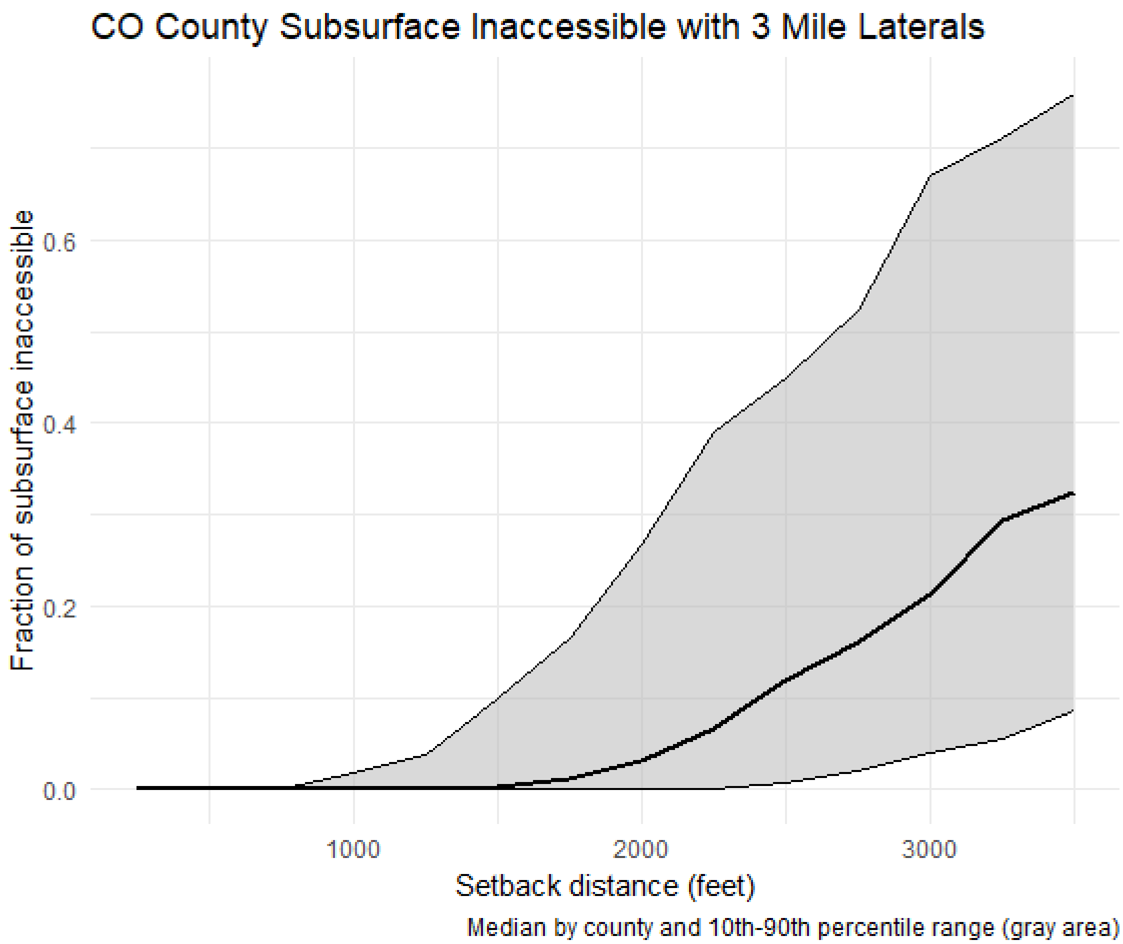
In Supporting Figure S3, we calculate the resource unavailability vs setback distance for counties in key oil and gas producing regions across the country. We see that these counties, which are broadly representative of oil and gas producing counties across the Unites States, produce an S-curve similar to Figure 5.

Washington and Susquehanna counties in Pennsylvania overlie the Marcellus formation. Tarrant County, TX overlies the Barnett Shale, while Martin County is in the Permian Basin. Williams County, ND lies in the Bakken. In addition to spanning geologies, these counties span population densities – Tarrant and Washington counties are quite dense and are part of the Dallas-Fort Worth-Arlington and Pittsburgh Metropolitan Statistical Areas, respectively. Susquehanna and Williams counties have moderate populations and population densities, while Martin County has a small and sparse population. In four of these counties, we see the familiar S-curve. In sparsely populated Martin County, setbacks have very little effect on resource availability, as one would expect in very low density areas.

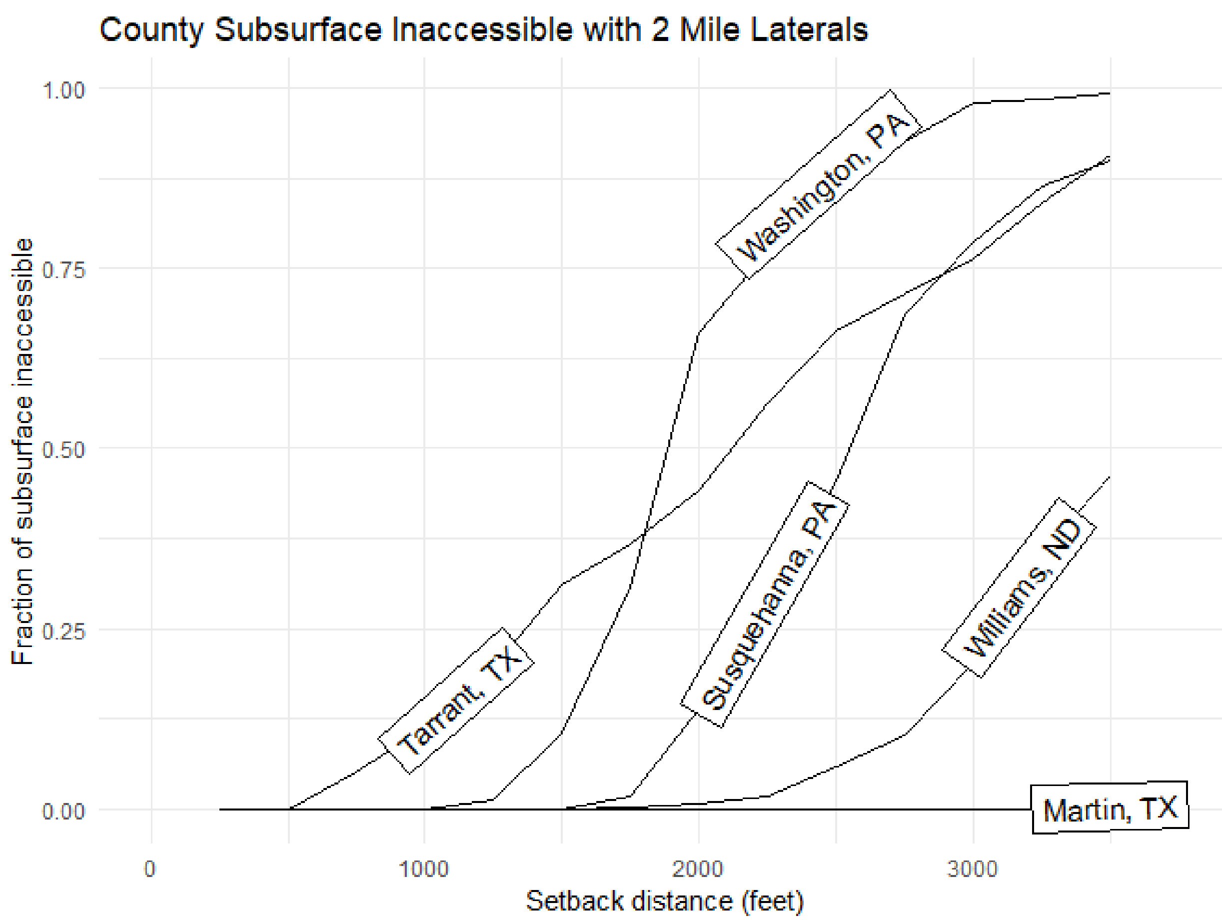
Additional Figures



Supporting Figure S1: Fraction of inaccessible subsurface area in Colorado counties. Calculation assumes two-mile horizontal drilling. Thick solid line represents median of 64 Colorado counties. Gray area illustrates 10^{th}-90^{th} percentile range.



Supporting Figure S2: Fraction of inaccessible subsurface area in Colorado counties. Calculation assumes three-mile horizontal drilling. Thick solid line represents median of 64 Colorado counties. Gray area illustrates 10th-90th percentile range.



Supporting Figure S3: Fraction of inaccessible subsurface area in key oil and gas counties in the US outside of Colorado. Calculation assumes two-mile horizontal drilling

Supporting References

1. Legislative Council of the Colorado General Assembly. *2018 State Ballot Information Booklet*. (2018). Available at: https://leg.colorado.gov/sites/default/files/2018_english_final_for_internet_1.pdf. (Accessed: 3rd July 2019)