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Authors
Deshmukh, Ranjit
Weber, Paige
Deschenes, Olivier
et al.

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Equitable low-carbon transition pathways for California's oil extraction

Ranjit Deshmukh[1,2,3*†], Paige Weber[2,4*†], Olivier Deschenes[2,5], Danae Hernandez-Cortes[2,6,7], Tia Kordell[1,2,8], Ruiwen Lee[1,2,8], Christopher Malloy[2,5], Tracey Mangin[1,2,8], Measrainsey Meng[2,3,8], Sandy Sum[1,2], Vincent Thivierge[1,2], Anagha Uppal[2,9], David W. Lea[10] and Kyle Meng[1,2,5*†]

[1]Bren School of Environmental Science and Management, University of California Santa Barbara, Bren Hall, Santa Barbara, 93106, California, United States.
[2]Environmental Markets Lab (emLab), University of California Santa Barbara, Bren Hall, Santa Barbara, 93106, California, United States.
[3]Environmental Studies Department, University of California Santa Barbara, Bren Hall, Santa Barbara, 93106, California, United States.
[4]Department of Economics, University of North Carolina, Gardner Hall, Chapel Hill, 27599, North Carolina, United States.
[5]Department of Economics, University of California Santa Barbara, North Hall, Santa Barbara, 93106, California, United States.
[6]School for the Future of Innovation in Society, Arizona State University, PO Box 876002, Tempe, 85287, Arizona, United States.
[7]School of Sustainability, Arizona State University, PO Box 877904, Tempe, 85287, Arizona, United States.
[8]Marine Science Institute, University of California Santa Barbara, Santa Barbara, 93106, California, United States.
[9]Department of Geography, University of California Santa Barbara, Ellison Hall, Santa Barbara, 93106, California, United States.
[10]Department of Earth Science, University of California Santa Barbara, Webb Hall, Santa Barbara, 93106, California, United States.

*Corresponding author(s). E-mail(s): rdeshmukh@ucsb.edu; paigeweber@unc.edu; kmeng@bren.ucsb.edu;
Contributing authors: olivier@econ.ucsb.edu; danae.hernandez-cortes@asu.edu; tiakordell@ucsb.edu; ruiwenlee@ucsb.edu; cmalloy@ucsb.edu; tmangin@ucsb.edu; mmeng@ucsb.edu; sandysum@ucsb.edu; vthivierge@bren.ucsb.edu; auppal@ucsb.edu; lea@geol.ucsb.edu;
†These authors contributed equally.

Abstract

Oil supply-side policies—setbacks, excise tax, and carbon tax—are increasingly considered for decarbonizing the transportation sector. Understanding not only how such policies reduce oil extraction and greenhouse gas (GHG) emissions but also which communities receive the resulting health benefits and labor market impacts is crucial for designing effective and equitable decarbonization pathways. Here, we combine an empirical field-level oil production model, an air pollution model, and an employment model to characterize spatially-explicit 2020–2045 decarbonization scenarios from various policies applied to California, a major oil-producer with ambitious decarbonization goals. We find setbacks generate the largest avoided mortality benefits from reduced air pollution and the largest lost worker compensation, followed by excise and carbon taxes. Setbacks also yield the highest share of health benefits and the lowest share of lost worker compensation borne by disadvantaged communities. However, currently proposed setbacks may fail to meet California's GHG targets, requiring either longer setbacks or additional supply-side policies.

Keywords: oil, transportation, emissions, energy justice, equity, California

Introduction

Across many industrialized economies, climate policies are increasingly focused on the transportation sector, which lags behind the level and pace of decarbonization observed in other sectors. Indeed, between 2010-2019, while non-transportation greenhouse gas (GHG) emissions have fallen by 6% across Organisation for Economic Co-operation and Development (OECD) countries, GHG emissions from transportation have risen by 6% [1]. Today, the transportation sector is responsible for the largest share of GHG emissions in the U.S. and the E.U. at 28% and 24%, respectively, and an even larger share in California (40%), the region of focus in this study [1, 2].

To date, transportation climate policy debates have primarily focused on demand-side policies to reduce fossil fuel consumption, such as fuel taxes, vehicle fuel economy standards, low carbon fuel standards, and electric vehicle subsidies [3–9]. In recent years, attention has turned towards supply-side policies that directly reduce fossil fuel production. These policies can take different forms. Some directly ban extraction from specific oil fields, such as oil well setbacks targeted at fields located near where people live and work. Other policies reduce extraction by targeting oil fields according to their extraction costs, either on a per barrel basis as with an excise (or severance) tax, or on a per GHG emissions basis as with a carbon tax. Thus, for the same overall GHG emissions target, different supply-side policies can generate distinct aggregate and distributional consequences by reducing production from different oil fields.

Two primary considerations arise when evaluating supply-side policies. The first is the relative effectiveness of each policy type in reducing oil production and associated GHG emissions, which to date has received limited empirical analysis [10–12]. The second pertains to the ancillary benefits and costs of each policy and how they are distributed across different communities. In particular, oil extraction tends to be highly spatially concentrated in certain areas, employing a local workforce and generating air pollution impacting nearby residents. Depending on how oil extraction is spatially located in relation to workers and households, different supply-side policies can have different aggregate and distributional consequences in terms of health benefits and labor market impacts. For example, for the same overall GHG emissions target, a policy that phases out more labor-intensive oil fields may have higher lost worker compensation than other policies. Likewise, a policy that bans oil fields near where disadvantaged households reside may generate larger overall health benefits and health equity gains. Quantifying such potential consequences is critical for informing the design of supply-side policies. More broadly, there is a need to understand if and how effectiveness in GHG emissions reductions and distributional consequences trade off across different oil supply-side policies.

Previous decarbonization studies employ either Integrated Assessment Models (IAM), which are combined energy, economy, and climate models [13, 14], or macro energy system models [15–17] that model regional energy systems. These models typically simulate or optimize energy infrastructure investments and retirements to meet certain GHG emissions reduction targets by assuming that fossil fuel extraction will be phased out and replaced by cleaner alternatives. Such models typically do not explicitly consider how specific supply-side policies (other than a carbon tax) can yield different decarbonization outcomes for fossil fuel extraction. Furthermore, most energy or economic models lack the fine spatial resolution needed to examine the distributional outcomes of alternative policies over time. For example, existing studies on the distributional and equity consequences of phasing fossil fuel production including oil extraction have only petroleum basin or county-level and not the oil field and census tract-level representation for fuel production and air pollution exposure, respectively [15, 18], which is critical to accurately estimate energy production, health effects, and equity outcomes of decarbonization pathways.

This paper examines the effectiveness and distributional consequences of potential supply-side policies intended to phase-out oil extraction across California. As the world's 5th largest economy and the U.S.' 7th largest oil producing state, California provides a unique setting to study supply-side policies. The state is currently implementing some of the world's most ambitious climate policies with a statewide carbon neutrality goal by 2045. This includes an active debate over various supply-side policies to dramatically reduce oil extraction, with an explicit interest in examining resulting labor and health equity consequences and their distribution across the state [19–21].We improve upon previous studies by developing an empirically-estimated model of crude oil well entry (drilling), production, and exit (retirement) at the oil field level, along with an air pollution model to quantify health effects at the census tract level, and an employment input-output model to determine employment impacts at the county level. We examine three supply-side policy interventions that have been widely debated in California and elsewhere: 1) well setbacks that require new oil wells to be located beyond a specified minimum distance from sensitive sites such as occupied dwellings, schools, healthcare facilities, and playgrounds; 2) an excise tax on each barrel of crude oil extracted; and 3) a carbon tax on GHG emissions from oil extraction. We find that a setback policy provides greater statewide health benefits but also larger lost worker compensation compared to a carbon or excise tax that achieves the same 2045 GHG emissions target. In general, setback policies also have better equity outcomes as disadvantaged communities accrue a larger share of health benefits and a smaller share of loss in worker compensation. By contrast, a carbon tax imposes the smallest statewide worker compensation loss amongst the three policies. Finally, currently proposed setback distances applied to only new wells will be unable to meet California's decarbonization goals. To do so requires setbacks with a distance greater than 1 mile, applied to both new and existing wells, and/or combined with a carbon or excise tax.

Crude oil production and GHG emissions pathways

We develop spatially and temporally-explicit pathways that reduce California's oil extraction in response to various supply-side interventions—well setbacks, excise tax, and carbon tax—between 2020–2045. Our approach has two components and is summarized in Fig. 1. For all oil fields in California (Fig. 1a), we first construct an empirically-estimated model of crude oil well entry (Fig. 1b), production, and exit at the oil-field level to project how various supply-side policies and macroeconomic conditions affect oil production across California oil fields out to 2045 (Methods section and Supplementary Note 8, Supplementary Note 9, Supplementary Note 10, Supplementary Note 11, Supplementary Note 17, and Supplementary Note 16). In our second step, we insert field-level predictions of oil production from our empirical model into: 1) an air pollution model, InMAP (Intervention Model for Air Pollution) [22], to characterize how air pollution emissions from oil fields disperse across the state (Fig. 1c,d, Supplementary Note 13), and 2) an employment input-output model, IMPLAN [23, 24]) which uses fixed multipliers to quantify local employment changes in the oil extraction sector ("direct"), in sectors that provide inputs to oil extraction ("indirect"), and in sectors where these workers spend income ("induced") (Fig. 1e, Supplementary Note 14). Together, these components provide an empirically-based analysis of how supply-side policies could alter not just oil production across oil fields, but also the spatial distribution of health impacts from air pollution and employment across California.

For well setbacks, we consider three setback distances—1,000 feet, 2,500 feet, and 1 mile—which encompass distances currently considered in policy proposals [25–28]. To ensure policy comparability, we set excise taxes as a percentage of oil price fixed across all years and carbon taxes which increase at an annual rate of 7% to levels that result in the same 2045 statewide GHG emissions as our three setback distance policies (See Supplementary Note 17). We further consider a fourth excise and carbon tax level that achieves a 90% GHG emissions reduction by 2045 compared to 2019 levels, inline with California's target for in-state finished fuel demand [2].

Each combination of policy intervention—setbacks, excise tax, and carbon tax—and 2045 annual GHG emissions target results in a unique spatial and temporal pattern of oil production, benefits, and costs. We model these patterns across California for the 2020–2045 period, focusing on avoided mortality due to reduced $PM_{2.5}$ emissions and avoided global climate damages from reduced GHG emissions on the benefits side, and lost earnings from the oil extraction sector on the cost side. We analyze these policy scenarios using a common benchmark projection of global oil prices out to 2045 (EIA's reference oil price projection [29]). Sensitivity analysis results using higher and lower projected oil prices are shown in the Supplementary Information.

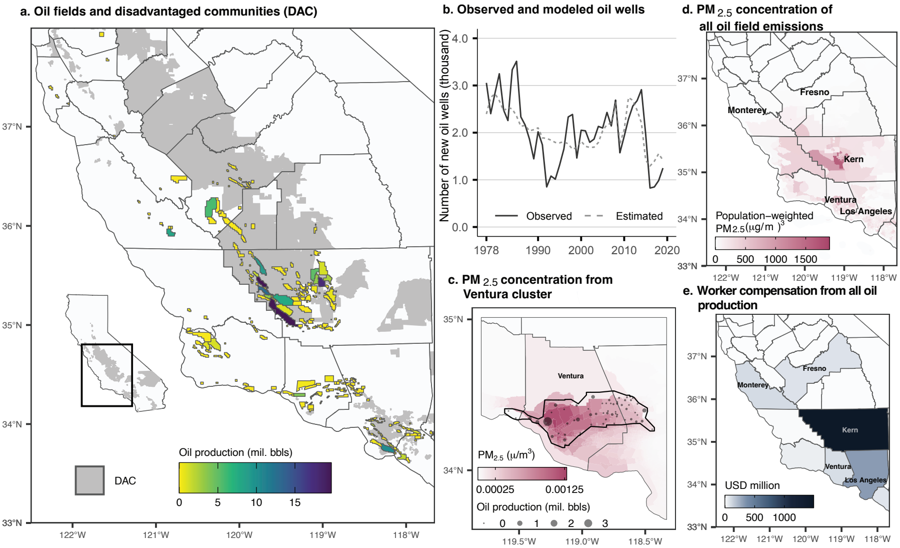

Fig. 1: **Summary of data and methods.** (a) Oil production in 2019 by field. Gray-shaded areas indicate census tracts with disadvantaged communities, as defined by CalEnviroScreen. (b) Observed and estimated historical oil well entry across California (Supplementary Note 9). (c) Particulate Matter ($PM_{2.5}$) concentration by census tract for a 1 tonne pulse of $PM_{2.5}$ emission from the Ventura cluster. Points indicate location of 2019 oil production from oil fields within the cluster. (d) $PM_{2.5}$ concentration by census tract associated with all 2019 oil production. (e) Worker compensation by county associated with all 2019 oil production.

California's oil production peaked in 1985 and has been declining since [30]. Our projection of statewide oil production to 2045 under a business-as-usual (BAU) scenario continues this trend (Fig. 2). In this no-supply-side policy BAU scenario, oil production in 2045 decreases by 57% compared to 2019 levels. Associated GHG emissions decline by 53%, which is well short of California's decarbonization targets.

Supply-side policies lower statewide crude oil production but with different temporal and spatial patterns (Fig. 2a, and Supplementary Fig. 17). Setbacks applied to new wells, excise taxes applied per unit of production, and carbon taxes applied per tonne of GHG emissions lead to continuous declines that outpace that of the BAU trajectory, albeit with different pathways. In general, a setback and an excise tax result in lower oil production in each year when compared with a carbon tax that is calibrated to achieve the same 2045 GHG emissions target. This is because a carbon tax on extraction emissions targets oil fields with higher GHG emissions intensities, whereas a setback targets oil fields in more populated areas and an excise tax targets production declines among more costly oil fields. Supplementary Fig. 1 shows that the relationship between production costs and emissions intensities is not systematic. As a result, the fields that reduce production under a carbon tax will be unique from the fields that reduce production under an excise tax that achieves an equivalent reduction in carbon emissions.

There is close correspondence between statewide oil production and emissions pathways (Fig. 2b). As with oil production, setbacks, excise taxes, and carbon taxes induce a continuous decline. By construction, because excise and carbon tax levels were calibrated to result in the same 2045 GHG emissions as the corresponding setback distances, the GHG emissions trajectories of setbacks, excise taxes, and carbon taxes are more closely aligned than oil production trajectories. Cumulative 2020–2045 GHG emissions reductions from carbon taxes are consistently lower than setbacks and excise taxes for each 2045 GHG emissions target, irrespective of the oil price projections (Fig. 2c and Supplementary Figs. 24, 25). However, excise taxes, depending on the tax level required to meet the GHG emissions target under different oil prices could have slightly lower or higher cumulative GHG emissions compared to setbacks. When considering alternative oil price projections, annual GHG emissions reduction in 2045 for a 1 mile setback is significantly lower (33%) under EIA's high oil price projection (Supplementary Fig. 24), while it nearly reaches the 90% reduction target under EIA's low oil price projection (89% reduction) (Supplementary Fig. 25).

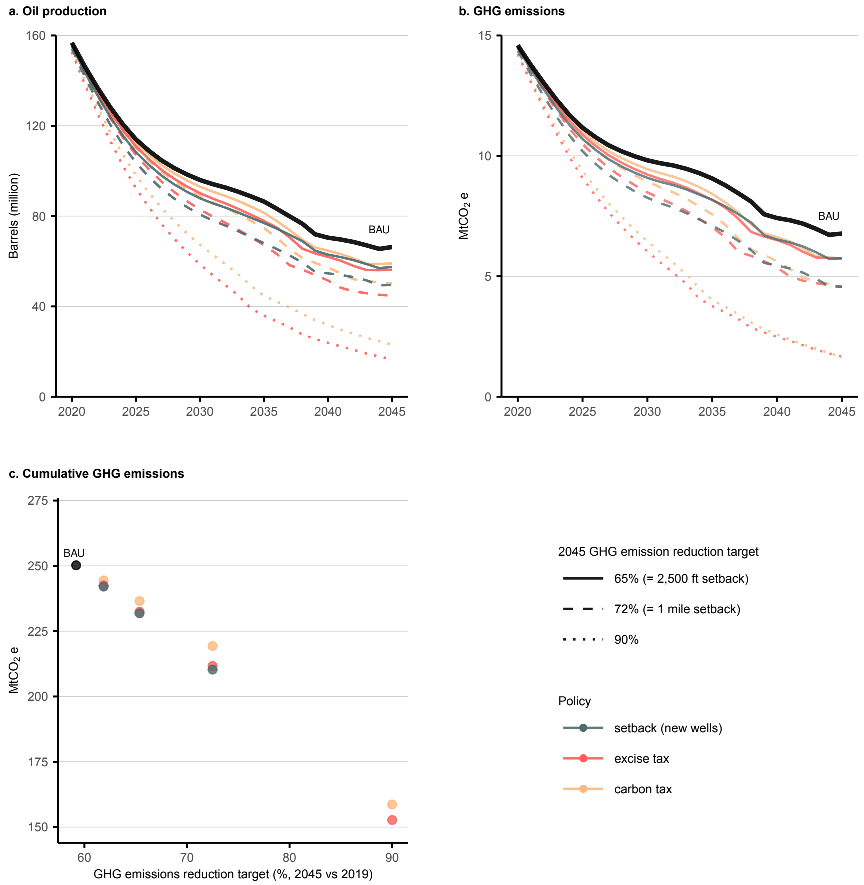

Fig. 2: **California crude oil production and associated greenhouse gas (GHG) emission pathways.** Annual California oil production and GHG emissions under business-as-usual (BAU) and three supply-side policies—setbacks applied to new wells, excise tax on oil production, and carbon tax on emissions from oil extraction. Excise and carbon taxes are calibrated to meet 62% (=1,000 ft setback), 65% (=2,500 ft setback), 72% (=1 mile setback), and 90% GHG emissions reduction by 2045 relative to 2020. (a) Crude oil production. (b) GHG emissions from crude oil production. (c) Cumulative 2020-2045 GHG emissions. Data for 62% GHG emissions reduction scenario (=1,000 ft setback) not shown in (a) and (b) for visual clarity. Setback distances are limited to 1 mile or below and thus, a setback that meets a 90% 2045 GHG emissions target is not modeled. Total number of oil fields in the model is 263.

Health, labor, and avoided climate change impacts

Reduced crude oil production from supply-side policies have associated health benefits, labor market impacts, and benefits from avoided climate change damages. We estimate statewide health benefits from cumulative avoided mortality resulting from lower air pollution levels, costs from lost total labor compensation, and benefits from avoided climate change damages due to abated GHGs, priced at the social cost of carbon [31], both total (Fig. 3a, b, and c) and per unit of cumulative avoided GHG emissions over 2020–2045 for each scenario (Fig. 3d, e, and f). The costs and benefits are relative to the BAU scenario and estimated in net present value terms, valued in 2019 US dollars (see Supplementary Note 13, Supplementary Note 14, and Supplementary Note 15).

We note that health benefits denominated in monetized avoided mortality from air quality improvements and lost worker compensation from oil extraction reported here do not provide a full account of statewide benefits and costs under each supply-side policy. Reductions in ambient air pollution can bring a wide range of health benefits, including reduced morbidity, asthma attacks, and other respiratory diseases, as well as lower hospital and medication expenses. For example, reduced activity in the oil and gas extraction sectors may reduce ground-level ozone concentrations which may lead to additional health benefits that are not accounted for in our study [32]. To the extent that other ambient air pollutants like ozone travel similarly to $PM_{2.5}$, the disadvantaged communities vs non-disadvantaged communities contrast in the estimated health benefits should be a reasonable approximation of the full health benefits comparison despite focusing only on primary and secondary $PM_{2.5}$.

We focus on monetized avoided mortality alone to measure the benefits of air quality improvements since the previous literature has shown that monetized avoided mortality is by far the largest benefit [33]. Premature mortality is also the health end-point for which there is the most scientific consensus supporting the causal link between air pollution (in particular $PM_{2.5}$) and the end-point [33]. There are also potential benefits associated with non-health impacts through changes in agricultural and labor productivity [34, 35]. Likewise, we are unable to account for the possible re-employment of oil extraction workers that may find employment in other sectors. Unfortunately, little is known on re-employment rates and wages for former oil extraction workers to inform such calculations. Thus, our estimates represent lower bounds of potential health benefits and upper bounds of potential employment and worker compensation losses. Lastly, considerable uncertainty exists in the value of the social cost of carbon, a key ingredient in how avoided climate damages are calculated [31]. For these reasons, we present our health, labor and avoided climate damage values separately in Fig. 3, without attempting to conduct

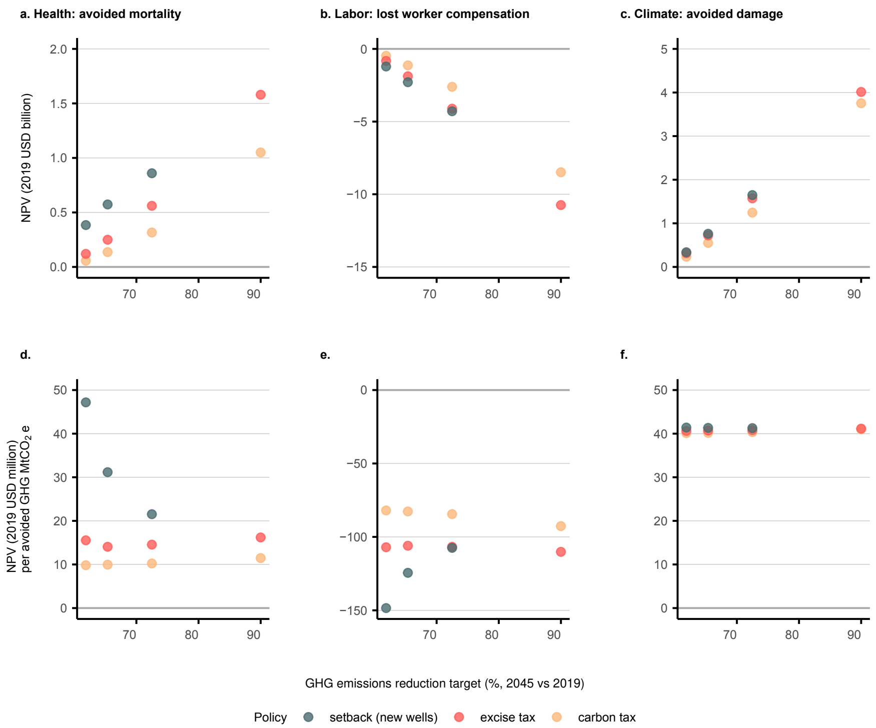

Fig. 3: **Health, labor, and climate impacts from California's oil production pathways under different policies relative to business-as-usual (BAU).** (a) Total health benefits from avoided mortality, (b) total lost worker compensation, and (c) avoided climate damages valued at the social cost of carbon over 2020-2045 under three supply-side policies—setbacks applied to new wells, excise tax on oil production, and carbon tax on emissions from oil extraction—relative to BAU to meet four 2045 GHG emissions targets. (d), (e), and (f) replicate (a), (b), and (c) but normalized by cumulative 2020-2045 GHG emissions. No setback distance equivalent to 90% 2045 GHG emissions target is applied. Total number of oil fields in the model is 263. Net present values are in 2019 U.S. dollars, estimated using a discount rate of 3%.

a full cost-benefit analysis. We instead focus on the relative rankings of each benefit and cost across the three supply-side policies examined.

Amongst policies, setbacks consistently achieve the greatest health benefits, both in total and per unit of cumulative avoided GHG emissions (Fig. 3a, d). This result validates the intent behind setbacks, a policy designed specifically for improving health outcomes by eliminating oil extraction from fields that are situated near residences, schools, and other locations where people live and work. However, per unit of cumulative avoided GHG emissions, longer distance setbacks yield smaller health benefits (Fig. 3d) because the marginal pollution from avoided wells affects a smaller number of people.

For statewide worker compensation losses, the pattern flips across supply-side policies. For a given 2045 GHG emissions target, setbacks consistently generate slightly higher worker compensation losses across the state than excise taxes, which exceed that for carbon taxes (Fig. 3b). This is because setbacks experience a drop in production larger than excise and carbon taxes designed to meet the same 2045 GHG emissions target and they affect wells in counties that have a higher employment intensity (jobs per barrel of oil produced). Excise taxes lead to greater worker compensation loss because they are less cost-effective at targeting GHG emissions reductions compared to carbon taxes, requiring a larger drop in oil production and associated employment losses to meet the same GHG emissions target. The ranking across policies is preserved when considering worker compensation losses per unit of cumulative avoided GHG emissions (Fig. 3e).

For avoided climate change damages, setbacks deliver slightly greater cumulative benefits for each 2045 GHG emissions target compared to excise and carbon taxes (Fig. 3c). These differences are even smaller across policies on a per unit of cumulative avoided GHG emissions basis (Fig. 3f).

The relative ranking for the health impacts from the three supply-side policies remains the same under the EIA's high and low oil price projections, although the average magnitude of these benefits and costs are correspondingly higher or lower than the reference EIA oil price projection (Supplementary Figs. 26 and 27). Cumulative lost worker compensation and avoided climate damages remain the lowest for carbon taxes across high and low oil price projections (Supplementary Figs. 26 and 27).

Drivers of health and labor outcomes across policies

The ranking of health benefits and labor costs shown in Fig. 3 across supply-side policies occurs because each policy targets different aspects of crude oil production and thus the sequence and timing of well entry, production, and retirements across oil fields. To explore this further, we sort oil fields according to the characteristic directly targeted by each policy. Specifically, these characteristics, shown on the x-axis across the columns of Fig. 4, include an oil field cluster's: (i) area share near sensitive sites, (ii) per barrel cost of extraction per barrel, and (iii) GHG emissions intensity per barrel. These characteristics are directly affected by a setback, an excise tax, and a carbon tax. Under each policy, oil fields on the left of the x-axis retire first, moving rightward as stringency tightens. For example, for a particular setback distance (2500ft in Fig. 4a and d), fields with a greater share of their area near sensitive sites will experience greater reduction in oil production than fields with areas less affected by the same setback. The latter fields that are farther from sensitive sites will be increasingly affected as setback distances increase. Likewise, under

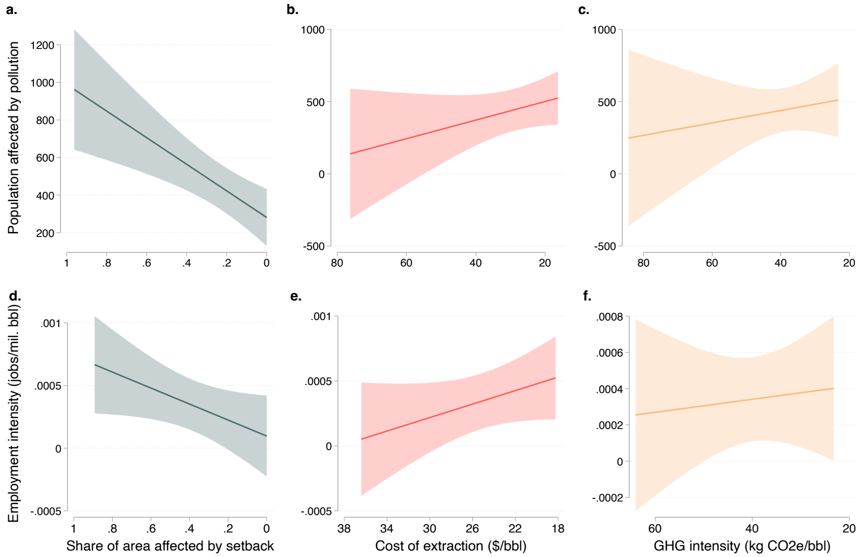

Fig. 4: **Correlations between health and labor impacts with oil-field characteristics.** (a)-(c): Correlation between statewide population affected by a 1 tonne pulse of particulate matter ($PM_{2.5}$) from an oil field cluster on the y-axis and that cluster's (a) share of area affected by setback (at 2500 ft), (b) cost of extraction (in U.S. dollars per bbl), and (c) greenhouse gas (GHG) intensity (in kg CO_{2e} per bbl) on x-axes. (d)-(f): replicates (a)-(c) but with employment intensity (in jobs per million bbls of oil produced) on the y-axis at the county level. Total number of oil fields in the model is 263. All oil field characteristics shown here are estimates from 2020. Shaded areas show 95% confidence intervals.

a low excise tax, the oil fields that initially phase out production are those with higher extraction costs. As the excise tax increases, oil fields with lower extraction costs incrementally phase out production. A similar pattern holds for carbon taxes and their effect on oil fields with varying GHG intensities.

To understand how policies differ in terms of statewide health benefits, the y-axis in the top panels of Fig. 3 shows the number of affected individuals per unit of pollution for each oil field on the y-axis. Because of the downward relationship shown in Fig. 4a, shorter distance setbacks initially affect oil fields that are upwind of more population-dense locations. As setback distances increase, the marginal oil field that is phased out is upwind of fewer people, explaining why the health benefit per unit of cumulative avoided GHG emissions falls with more stringent setbacks (Fig. 3d). By contrast, the relationships between population affected by pollution and costs of extraction and GHG intensity of oil fields are both upward sloping (Figs. 4b and c). This is reflected in the increasing health benefits, in both total and per unit of cumulative avoided GHG emissions, with increasing stringency of excise and carbon taxes (Fig. 4a and d). In other words, as excise and carbon taxes increase, the marginal oil field that exits production is upwind of more people.

To understand patterns in labor market impacts, we explore correlations between employment intensity in the oil extraction sector at the county level in total job losses per million barrels of oil produced, and the three oil field characteristics (Fig. 4d-f). The employment impacts reported in this study are driven by IMPLAN multipliers that account for direct, indirect, and induced jobs. As shown in Fig. 4, oil fields that are more impacted by setbacks have a greater employment intensity (jobs per million barrels), reflecting larger multipliers and county population. For example, oil fields in Los Angeles county are affected more by shorter setbacks because a larger population in the county lives close to oil fields, but they also create more direct, indirect, and induced jobs based on IMPLAN's data. The downward relationship in Fig. 4d explains why employment loss per GHG emissions reduction is the highest at shorter setback distances (Fig. 3D). Shorter setbacks induce more labor intensive oil fields to exit production first, followed by less labor intensive fields as setback distances increase. Again, by contrast Figs. 4e and f are upward sloping, indicating that with excise and carbon taxes, less labor intensive oil fields go out of production first. This is consistent with statewide labor costs, in both total and per unit of cumulative avoided GHG emissions basis, increasing (more negative) in Figs. 4b and e as excise and carbon tax stringency increases. Higher excise and carbon taxes incrementally induce more labor intensive fields to go out of production.

County-level outcomes are similarly driven by county and oil field characteristics. Comparing California's three highest oil producing counties in 2019, production in Los Angeles county has lower average costs per barrel and lower average GHG emissions intensity compared to Kern or Monterey (Supplementary Figs. 19 and 20), but greater health impacts (mortality) and employment intensity per barrel of oil production (Supplementary Figs. 21, 22, 23). Under a setback policy, oil production in denser Los Angeles county is affected more than Kern and Monterey counties (Supplementary Fig. 18), which results in greater health benefits but also higher labor impacts compared to the excise and carbon tax policies. Because the average cost of oil production and GHG emissions intensities in oil fields in Kern and Monterey counties are greater than Los Angeles county, both the excise and carbon tax policies result in lower health benefits and labor impacts compared to the setback policy.

Equity impacts of supply-side policies

To understand the equity impacts of supply-side policies, we examine how the statewide health and labor consequences of each decarbonization pathway are distributed spatially across the state. We use California's legal definition of whether a census tract is a "disadvantaged" community (DAC) using

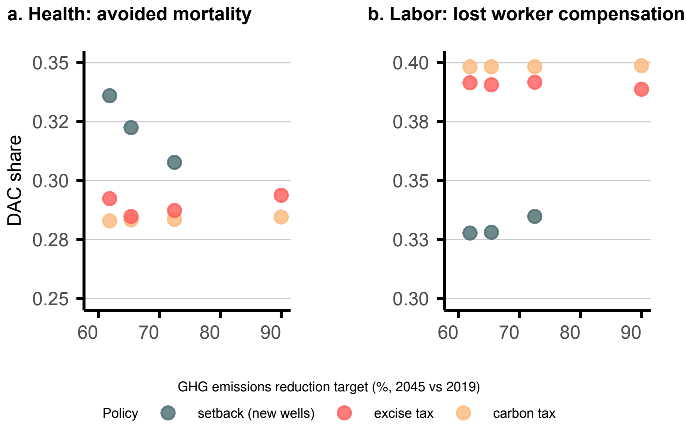

Fig. 5: **Disadvantaged communities' share of health and labor impacts.** (a) Share of avoided mortality benefits borne by individuals and (b) share of foregone oil extraction earnings borne by workers in disadvantaged communities under setbacks, excise tax, and carbon tax for different 2045 greenhouse gas (GHG) reduction targets.

CalEnviroScreen, a scoring system based on multiple pollution exposure and socioeconomic indicators developed by the California Environmental Protection Agency [36]. For each policy scenario, we estimate the share of the total statewide health benefits and employment losses in oil extraction borne by communities living in disadvantaged community census tracts (Figs. 5a and b).

The disadvantaged communities' share of health benefits is consistently larger under a setback than under excise and carbon taxes for a given 2045 GHG emissions target. This share is largest at lower setback distances, or equivalently less stringent 2045 GHG emissions targets, and decreases as the setback distance increases. For excise and carbon taxes, the disadvantaged communities' share of benefits is relatively unaffected by the stringency of the 2045 GHG emissions target. The lost worker compensation is largest for setbacks at the statewide level. However, the share of total lost worker compensation from workers in disadvantaged communities is consistently lower under setbacks than under excise and carbon taxes. Thus, for any given 2045 GHG emissions target, a greater share of health benefits and a lower share of worker compensation impacts are experienced by DACs under a setback than under excise and carbon taxes. This result holds even under the EIA's high and low oil price projections (Supplementary Figs. 28 and 29).

Setbacks applied to all versus only new wells

Although most existing and proposed setback policies apply to only new wells, applying setbacks additionally to existing wells could be an important policy instrument to further mitigate GHG emissions and improve health outcomes of neighbouring communities that have historically borne the burden of local pollution from oil extraction. To understand the health, labor, and equity consequences of setbacks on all wells, we also model a setback policy that affects both new and existing wells applied in 2020.

In comparison to setbacks on only new wells, applying setbacks to all wells predictably results in greater oil production declines and emission reductions. As discussed earlier, setbacks applied to only new wells result in a continuous decline in oil production and GHG emissions (Fig. 6). In contrast, setbacks applied to all wells induce an immediate drop in statewide oil production and associated GHG emissions in 2020 as existing wells within the setback distance fall out of production. This drop is then followed by a gradual decline thereafter that tracks the BAU trajectory. Oil production and GHG emissions reductions increase as setbacks get longer. Although a 1 mile setback, the largest considered in this study, applied to all wells achieves a significantly greater GHG emissions reduction (81%) by 2045 compared to the same setback on new wells (72%), it still falls short of meeting the 90% reduction target (Fig. 6b). However, the cumulative GHG emissions reduction over 2020–2045 for the 1 mile setback applied to all wells is on par with those of excise and carbon taxes that result in a 90% annual GHG emissions reduction in 2045 (Fig. 2c).

Setbacks applied to all wells result in fewer premature deaths, but also greater total lost worker compensation compared to setbacks on only new wells (Fig. 6). Setbacks on all wells have better equity outcomes by accruing a greater share of avoided mortality benefits and a lower share of lost worker compensation to disadvantaged communities. Thus, setbacks applied to all wells in general would yield more pronounced health and labor market consequences than setbacks applied to just new wells.

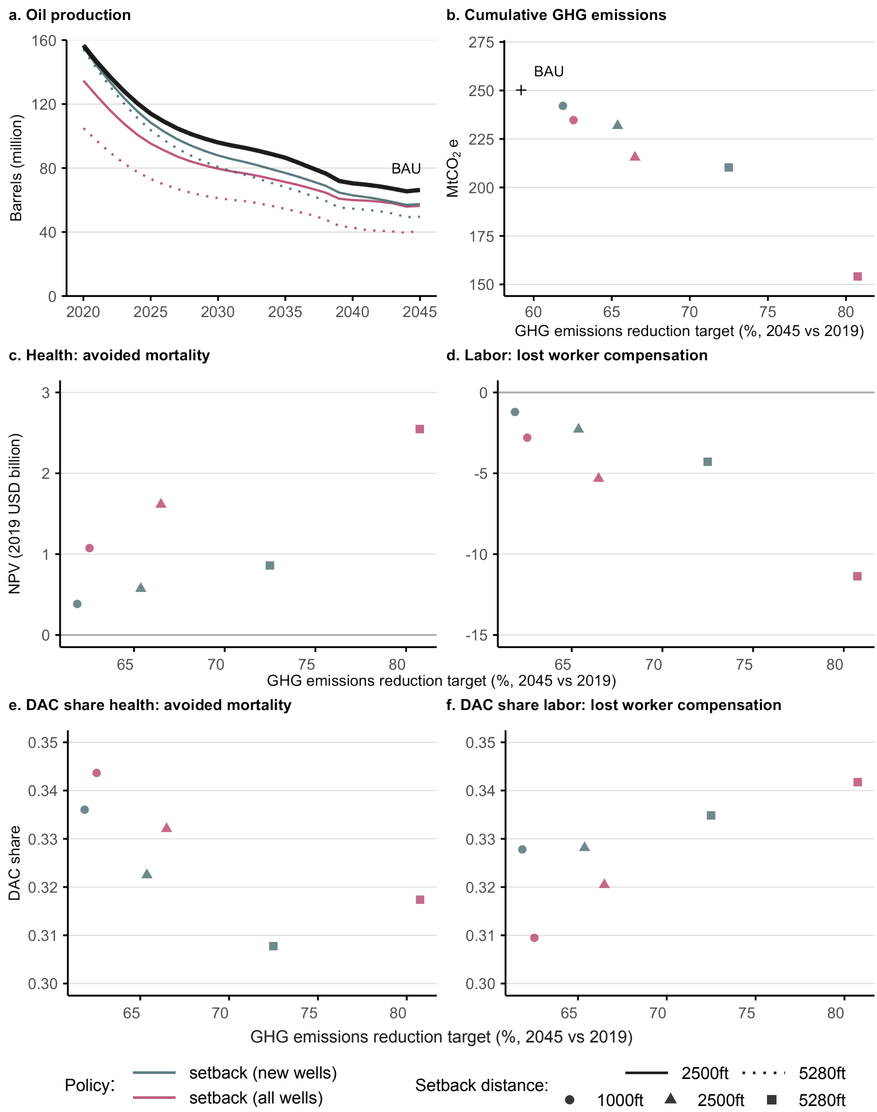

Fig. 6: **Comparison between setback policies applied to new and all wells.** Three setback distances—1,000 ft setback, 2,500 ft setback, and 1 mile setback—applied to new and all (new and existing) wells. (a) Oil production pathways, (b) cumulative greenhouse gas (GHG) emissions over 2020-2045, (c) total health benefits from avoided mortality, (d) total lost worker compensation, (e) share of avoided mortality benefits borne by individuals in disadvantaged communities, and (f) share of foregone oil extraction earnings borne by workers in disadvantaged communities under the three setbacks. Total number of oil fields in the model is 263. Net present values are in 2019 U.S. dollars, estimated using a discount rate of 3%.

Discussion and conclusions

By quantifying the tradeoffs across different supply-side policies, we find that for California an oil well setback policy applied to new wells provides greater health benefits compared to a carbon or excise tax policy designed to achieve the same 2045 GHG emissions reduction target. A setback policy also produces equity gains as disadvantaged communities accrue greater health benefits and lower employment costs under a setback than other communities compared with excise and carbon taxes.

Yet, a setback policy imposes the largest statewide loss of worker compensation amongst the three policies for the reference oil price projection. Moreover, on its own, a setback policy applied to new wells achieves only a 72% GHG emissions reduction in 2045 compared to 2019 for a 1 mile setback, a distance larger than the maximum 3,200 ft currently proposed in California [28]. GHG emissions reductions would be even lower under higher global crude oil prices. While a setback policy is generally advocated by stakeholders based on public health concerns, it will need to either impose greater distances, be applied to both new and existing wells, or be combined with an appropriate excise or a carbon tax in order to meet California's decarbonization goals (Supplementary Figs. 30, 31, 32, 33, 34, and 35).

Whereas carbon taxes and excise taxes are both able to achieve more aggressive annual GHG emissions reductions, i.e. 90% GHG emissions reduction by 2045 compared to 2019, the tax values required to achieve 90% decarbonization are higher compared to those considered in current policies. The carbon tax required to drive a 90% GHG emissions reduction by 2045 starts at USD 250 per tCO_{2e} in 2020 and increases to USD 1,330 per tCO_{2e} in 2045. This trajectory is nearly four times higher than the allowance price ceiling under California's cap-and-trade system which starts at USD 65 per tCO_{2e} in 2021 and rises to USD 330 per tCO_{2e} by 2045, assuming an annual real growth rate of 5% and an inflation rate of 2% [37]. Similarly, none of the excise taxes currently in effect across 27 U.S. states exceed 10% of the oil price [38], which is far lower than the 67% tax we find is required to achieve a 90% GHG emissions reduction target by 2045 under EIA's reference oil price projection.

Finally, our results indicate that combining a setback with a carbon tax could achieve the state's GHG emissions target while yielding greater statewide health benefits, lower statewide worker compensation losses, and larger equity gains compared with having just a carbon tax or excise tax alone. However, if the setbacks are applied to only new wells, the carbon tax trajectory would still need to be three times higher than currently permitted under California's cap-and-trade system (Supplementary Fig. 16). For the two trajectories to be similar, setbacks would need to be applied to both existing and new wells.

Although we only examined the impacts of $PM_{2.5}$ on health outcomes, oil extraction also emits other toxic pollutants, including benzene, ethylbenzene, and n-hexane, which are known to cause cancer and other serious health effects

[39]. Setbacks will not only reduce exposure to $PM_{2.5}$ pollution but will also decrease exposure to these other toxic pollutants and thus could lead to larger health benefits as oil extraction is phased out. To realize the health and climate benefits of setbacks estimated in this study, setbacks will need to be applied to both existing and new wells, unlike most existing and proposed regulations that apply setbacks to only new wells.

Two other supply-side policies that we do not examine in this study include limiting producer subsidies [14, 40] and restricting development of oil fields, either by compensating resource owners for not exploiting their fuel resources, buying and retiring resource rights, or limiting new leases on government lands [10, 41]. The former is similar to imposing an excise tax on production, whereas the latter requires rules to prioritize fields for constraining development, similar to a setback policy that is considered in this study.

The effectiveness and equity tradeoffs across various oil supply-side policies must be ultimately considered in tandem with oil demand-side policies, without which global GHG emissions reductions may be limited when oil markets are global. For example, demand-side policies from any jurisdiction alone may yield limited GHG emissions reductions if other jurisdictions increase oil demand in response to lower global oil prices [11, 42, 43]. Similarly, only restricting oil supply in a single jurisdiction without efforts to limit oil demand in that jurisdiction will result in an increase in oil exports from elsewhere, with some amount of local GHG emissions reduction replaced by increased GHG emissions elsewhere. By coordinating oil supply- and demand-side policies, it is possible for a jurisdiction's oil supply and demand curves to jointly shift in a manner that leaves the global oil price unchanged and avoid GHG leakage to other jurisdictions.

Additionally, demand and supply policies that simply reduce GHG emissions from transportation fuels may have limited GHG emissions reductions if there is not an economy-wide climate policy, such as a carbon price, that ensures any energy source that replaces oil for transportation, such as electricity, is not more carbon intensive. For example, a transition from oil to electricity in transportation may have limited climate benefits if the electricity is produced primarily by coal. Future research should assess the resulting effectiveness and equity consequences of having multiple complementary climate policies.

Such future analyses can take advantage of the methodological approach developed in this paper. Across many settings and sectors, stakeholders are asking decarbonization policies to take into account not just their GHG emissions consequences, but also how the local costs and benefits of these policies are distributed spatially and across different demographic groups. This paper provides a step forward in that direction by combining an empirical-based, spatially-explicit energy production model with state-of-the-art air pollution transport modeling to quantify health benefits at a fine spatial scale as well as an employment model to quantify local labor market consequences. Our framework can be applied to other decarbonization policies at various scales such as studying the distributional consequences of decarbonizing other forms of fossil fuel extraction, electricity production, or manufacturing activity. More broadly, in many settings that already exhibit socioeconomic inequities, there is an increasing need to understand whether decarbonization policies itself would exacerbate or narrow such inequities. This study and its methodology provides a path forward for such analyses.

Methods

Modeling framework

To estimate the health and labor consequences of supply-side policies, we build an empirically validated model of oil production to estimate field-level oil production and GHG emissions pathways under varying policy scenarios. These estimates drive our projections of pollution dispersion, mortality effects, and local employment, which are used to quantify health and labor impacts under different policy and GHG emissions target scenarios. We further examine the equity impacts of these scenarios focusing on how health and labor impacts are distributed between disadvantaged and other communities. Throughout, we use nominal prices in both the estimation and projection parts of the analysis. When presenting health and labor impacts, we calculate net present discounted values in 2019 dollars after applying a discount rate of 3% and an inflation rate of 2%.

Supply-side policies and oil price forecasts

We model the impacts of three policies—setbacks, excise tax, and carbon tax—on California's oil sector. A setback policy prohibits oil (and gas) extraction within a specified distance from sensitive sites including occupied dwellings, schools, healthcare facilities, and playgrounds. We model two setback scenarios – 1) setbacks that apply to new wells only (main results) and 2) setbacks that apply to new and existing wells, or all wells. We model setbacks on new wells by proportionally reducing field-level future new well entry based on the relative field area covered by a given setback buffer. For existing wells, setbacks are implemented in our model by removing those within the setback distance from future production. We consider setback distances of 1,000 ft, 2,500 ft, and 1 mile. We assume only vertical drilling in the setback analysis. Horizontal and directional drilling from pads outside of the setback distance could access additional sub-surface oil resources within the setback distance, reducing our estimates of the health and equity benefits of setbacks, especially for shorter setback distances [44]. However, the costs and extent of adoption of horizontal drilling are uncertain for California, and thus, not included in this study. The excise tax policy imposes a tax on each barrel of crude oil extracted. In our projection period, we apply a constant tax rate to the oil price each year. This is consistent with historical proposals for excise taxes on California oil extraction [45]. The carbon tax policy imposes a tax on the GHG emissions from the oil extraction site. We consider only direct GHG emissions, excluding methane emissions due to a lack of reliable oil field-specific data. All carbon tax trajectories increase at an annual rate of 7%, the sum of a 5% real growth rate and 2% inflation rate per year [46]. We determine the excise tax rates applied to the oil price and carbon taxes that result in the following 2045 statewide GHG emissions targets using an optimization function: 1) 2045 statewide GHG emissions associated with the three setback distances (Supplementary Table 4); and 2) a 90% reduction in statewide GHG emissions compared to 2019. The excise and carbon taxes are shown in Supplementary Figs. 15 and 16 and are inputs to the oil extraction model and affect future well entry and exit. See Supplementary Note 17 for more details.

For 2020–2045 macroeconomic conditions, we assume three Brent spot crude oil nominal price trajectories (reference, low, and high) obtained from the EIA's Annual Energy Outlook (AEO) 2021 forecast (Supplementary Fig. 13) [29]. For scenarios that do not include a carbon tax, we apply a baseline nominal carbon price equal to California's cap-and-trade allowance price floor (Supplementary Fig. 14). See Supplementary Note 16 for more details.

Oil production model

The model of oil production has three components: (1) well entry, (2) annual production after entry, and (3) well exit.

We model new well entry by estimating a Poisson model of well entry using data on historical production from existing wells and fields, costs, and crude oil nominal prices. Specifically, we estimate annual new well entry in an oil field as a function of oil prices, field-level capital and operational expenditures (Supplementary Figs. 2, 3 and 4), and field-level depletion. See details in Supplementary Note 9. This model is estimated using well entry data between 1977 - 2019 from California's Department of Conservation's WellSTAR database [47]. See Supplementary Note 1, Supplementary Note 3, Supplementary Note 4, and Supplementary Note 5 for more information on the input data. Capital and operational expenditure data are from the subscription based data provider Rystad Energy (Supplementary Note 2). Model estimates are provided in Supplementary Table 1.

After estimating the well entry model, we predict annual well entries for the 2020–2045 projection period using forecasted nominal prices and prescribed policy conditions. Field-level operational costs are modified each year based on the relevant carbon and excise tax. The setback policy constrains projected new well entry in a given field by reducing the number of predicted new wells by the percentage of field-area covered by a setback. Fig. 1 and Supplementary Fig. 5 compare the predicted and observed entry at the state level and for each top field category, respectively.

To predict annual oil production after well entry, we estimate oil production decline curves at the field and vintage level for both existing (i.e., pre–2020 entry) and new wells (i.e., wells that enter during 2020–2045). Production from oil wells often follow a declining profile of production until the wells exit

[48, 49]. For existing wells, we estimate the decline curve parameters using historical oil production data (see Supplementary Note 10) and apply them to the decline curve equations to estimate future annual production at the field-vintage level. To predict future production from new wells, we extrapolate historical parameters using a linear regression model to obtain values for the 2020–2045 forecast period. In each forecast year, for each field we use the corresponding extrapolated decline parameters and decline curve equations to determine field-vintage level production from the year the wells enter through the end of the projection period. We repeat this process for all forecast years. Modeled production decline curves and actual production for two fields are shown in Supplementary Figs. 6 and 7.

Because most wells that idle for a long time stop producing altogether [50], we use historical data on wells that idled continuously for ten years as a proxy for wells that stop producing and exit. We model well exits as a function of the nominal oil price, nominal field-level operational costs, and field-level depletion. We estimate the parameters of the model using historical data from 1977–2019 and apply the parameters to predict future well exit in the period 2020–2045, again, modifying field-level operational costs each year based on the relevant carbon and excise taxes. See Supplementary Note 11 for details. Model estimates are provided in Supplementary Table 1. Supplementary Figs. 8 and 9 compare the predicted and observed exit at the state level and for each top field category, respectively.

To account for well exits and setbacks, we adjust the predicted production from both existing and new vintages. We assume that each well in a given field-vintage produces the same amount of oil. Each year the exit model predicts the number of wells that exit from each field. We then remove these wells in order of vintage, starting with the oldest. For vintages that experience well exit, future production is correspondingly decreased to account for the reduction in number of wells in production. Similarly, for existing vintages we adjust predicted production to account for wells prohibited from future production due to setbacks by reducing production volumes proportionally by the number of wells removed by the setback. See Supplementary Note 8 for more details about the oil production model.

GHG emissions

We estimate GHG emissions associated with oil extraction using field-specific GHG emissions factors. We first estimate historical GHG emissions factors using the Oil Production Greenhouse Gas Emission Estimator (OPGEE) model v2.0 from the California Air Resources Board (CARB) [51, 52] (see Supplementary Fig. 10 for 2015 data). The OPGEE model is an engineering-based life cycle assessment tool for the measurement of GHG emissions from the production, processing, and transport of crude oil. Using the OPGEE model and oil extraction data from the California Department of Conservation (DOC), we model field-level GHG emissions for the years 2000, 2005, 2010, 2012, 2014, 2016, and 2018. We consider only upstream emissions from exploration, drilling, crude production, surface processing, maintenance operations, waste treatment/disposal, and other small sources (as modeled by OPGEE). To obtain emissions factors for oil fields that were not modeled by OPGEE, we apply the median emissions factors for the fields that were modeled, separated by the use of steam injection (see the Supplementary Note 12 for more information). To estimate the field-level GHG emissions for the projection period (2020–2045), we average the historical emissions factors for each year, again separated by fields based on the use of steam injection. We then linearly regress the average emissions factors and extrapolate over the projection period. Lastly, we apply the percent change in emissions factor between each forecast year to the field-level historical emissions factors from 2018 onward to determine field-level emissions factors for each forecast year. See Supplementary Note 12 for more details.

Health impacts

We first estimate $PM_{2.5}$ emissions from oil production for each oil field cluster (a set of oil fields clustered by geographical proximity; Supplementary Fig. 11) using average emissions factors obtained from a nation-wide U.S. sample [53] (Supplementary Table 2). Using average $PM_{2.5}$ emissions factors is a limitation of the study due to the lack of field-specific $PM_{2.5}$ emissions factors. In practice, actual emissions factors are likely highly heterogeneous across oil fields. Emissions factor heterogeneity can arise from differences across $PM_{2.5}$ emissions sources - which include on-site fossil fuel combustion from processing plants, generators, pumps, compressors, and drilling rigs, flaring, gas venting, dust from heavy vehicles, and secondary formation from ambient conditions - and across well vintages and operators [53, 54]. Whether such heterogeneity is consequential for air quality disparities should be a subject of future research as field-level emissions data become available.

Next, we model pollution dispersal using the Intervention Model for Air Pollution (InMAP) to obtain $PM_{2.5}$ concentration from oil production at the census tract level for each projection year [55]. InMAP is a reduced-complexity dispersal model based on the WRF-Chem model that models secondary $PM_{2.5}$ concentrations developed by [22]. We followed the methods by [55] and ran InMAP individually for each cluster and pollutant combination to obtain a source receptor matrix for all the extraction clusters. We then quantify the avoided mortality associated with changes in ambient $PM_{2.5}$ exposure at the census tract level compared to the BAU scenario [56, 57] using a mortality concentration-response function, adapted from [58]. This function estimates avoided mortality using population projections (Supplementary Fig. 12), a baseline mortality rate from 2015, the percentage change in mortality associated with a 1 $\mu g/m^3$ increase in $PM_{2.5}$ exposure (0.0058 from [59]), and our estimated changes in ambient concentrations of $PM_{2.5}$. Lastly, we estimate the monetized values of avoided mortality using a \$9.4 million (in 2019 USD) value obtained from [60]. All mortality benefits are then summed over the 2020–2045 projection period and presented in net present value terms. See Supplementary Note 6 and Supplementary Note 13 for more details.

Labor impacts

We quantify changes in employment and worker compensation using an economic input-output model from IMPLAN [61, 62]. IMPLAN uses over 90 sources of employment data to construct measures of county-level employment and compensation based on sector-specific revenue inputs. Supplementary Table 3 summarizes the input specifications for the labor analysis. Oil production and oil prices from the projected pathways serve as the inputs to IMPLAN, which then computes resulting employment in full-time equivalent job-years and total employee compensation supported by the oil and gas industry for each county with active oil and gas operations in the state. IMPLAN uses fixed multipliers to quantify local employment changes in the oil extraction sector ("direct"), in sectors that provide inputs to oil extraction ("indirect"), and in sectors where these workers spend income ("induced"). Similar to other input-output models, IMPLAN is based on a static framework where the underlying multipliers are fixed and do not change with the economic environment, which is a limitation of this model. This implies, for example, that inflation, changes in labor productivity, and geographical or temporal shocks to labor markets, all of which could be the result of some of the supply-side policies we consider, cannot be incorporated in the labor market impact analysis. See Supplementary Note 7 and Supplementary Note 14 for more details.

Equity impacts

To quantify distributional impacts, we use California's legal definition of a "disadvantaged" community (DAC) using CalEnviroScreen, a scoring system based on multiple pollution exposure and socioeconomic indicators developed by the California Environmental Protection Agency [36]. The following indicators are considered for the disadvantaged community definition: ozone concentration, $PM_{2.5}$ concentration, diesel emissions, pesticide use, toxic releases, traffic, drinking water quality, cleanup sites, groundwater threats, hazardous waste facilities, impaired water bodies, solid waste sites, asthma rate, cardiovascular disease rate, low birth weight percent, educational attainment, housing burden, linguistic isolation, poverty percent, and percent unemployed. A census tract is considered disadvantaged if it has a CalEnviroScreen score above the top 25^{th} percentile [63]. We calculate the disadvantaged communities ratio of health and labor impacts (i.e., the share of impacts experienced by disadvantaged communities) by calculating the ratio of the impact experienced by disadvantaged community census tracts to the total statewide impact. See Supplementary Note 18 for more details. Supplementary Note 19 and Supplementary Figs. 36 and 37 show the advantages of finer spatial resolution analysis (census tract level) and the errors that may be introduced by a coarser analysis conducted at the county-level, especially in the ranking of equity outcomes.

Data availability

Data on assets and asset-level costs from Rystad Energy and employment and worker compensation data from IMPLAN are proprietary. All other datasets are publicly available and were collected online from California's Department of Conservation (DOC), Energy Information Administration (EIA), International Energy Agency (IEA), and California Air Resources Board (CARB), Office of Environmental Health Hazard Assessment (OEHHA), California Department of Finance (CDOF), the Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE), National Historical Geographic Information System, Congressional Budget Office, InMAP, and the Census. All publicly available datasets are available on Zenodo at https://doi.org/10.5281/zenodo.7742802 with the exception of InMAP and BenMAP-CE data, which the user could download directly from the software. The Zenodo repository includes raw input data files that are not proprietary, intermediate data files to run the models, and final results files to create the figures. A detailed readme file includes descriptions of all data used in the study.

Code availability

All code used to conduct the study is available at https://github.com/emlab-ucsb/ca-transport-supply-decarb.

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Declarations

The authors declare no competing interests.

Contributions

R.D., P.W., K.M., O.D., and D.L. conceptualized the study and acquired the funding. R.D., P.W., K.M., O.D., D.H.C., R.L., C.M., T.M., M.M., and V.T. developed the methodology and software. R.D., P.W., K.M., O.D., D.H.C., R.L., C.M., T.M., M.M., S.S., V.T., and A.U. conducted the formal analysis. D.H.C., R.L., C.M., T.M., M.M., S.S., V.T., and A.U. curated the data. R.D., P.W., K.M., O.D., D.L., D.H.C., T.K., R.L., C.M., T.M., M.M., and V.T. wrote and edited the paper. K.M., O.D., D.L., P.W., and R.D. supervised the project.

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