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## Quantifying the social equity state of an energy system: environmental and labor market equity of the shale gas boom in Appalachia

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## LETTER

# Quantifying the social equity state of an energy system: environmental and labor market equity of the shale gas boom in Appalachia

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Erin N Mayfield<sup>1</sup> , Jared L Cohon<sup>2</sup>, Nicholas Z Muller<sup>2</sup> , Inês M L Azevedo<sup>3</sup> and Allen L Robinson<sup>2,4</sup> <sup>1</sup> Princeton University, Princeton, New Jersey, United States of America<sup>2</sup> Carnegie Mellon University, Pittsburgh, Pennsylvania, United States of America<sup>3</sup> Stanford University, Palo Alto, California, United States of America<sup>4</sup> Author to whom correspondence may be addressed.E-mail: [alr@andrew.cmu.edu](mailto:alr@andrew.cmu.edu)**Keywords:** energy systems, natural gas, equity, air quality, climate change, labor marketsSupplementary material for this article is available [online](#)

## Abstract

A fundamental societal concern in energy system transitions is the distribution of benefits and costs across populations. A recent transition, the US shale gas boom, has dramatically altered the domestic energy outlook and global markets; however, the social equity implications have not been meaningfully assessed and accounted for in public and private decision making. In this study, we develop and demonstrate a systematic approach to quantify the multi-dimensional equity state of an energy system, with a focus on the shale gas boom in the Appalachian basin. We tailor variants of standard equity metrics as well as develop new empirical and analytical methods and metrics to assess spatial, temporal, income, and racial equity as it relates to air quality, climate change, and labor market impacts across the natural gas supply chain. We find moderate to high spatial inequities with respect to the distribution of production (Gini coefficient ( $\eta$ ) = 0.93), consumption for electric power generation ( $\eta$  = 0.68), commercial, industrial, and residential end use ( $\eta$  = 0.72), job creation ( $\eta$  = 0.72), and air pollution-related deaths ( $\eta$  = 0.77), which are largely driven by geographically-fixed natural gas abundance and demand. Air quality impacts are also regressive, such that mortality risk induced by natural gas activity generally increases as income decreases; for example, mortality risk ( $m$ ) (in units of premature mortality per 100 000 people) for the lowest income class (<\$15 000;  $m$  = 0.22 in 2016) is higher (18%–31%) than for the highest income class (>\$150 000;  $m$  = 0.27 in 2016). These risks are higher for white ( $m$  = 0.30 in 2016) than non-white ( $m$  = 0.16 in 2016) populations, which is largely a result of the demographics of rural communities within the vicinity of natural gas development. With respect to local labor market impacts within producing counties, we find marginal declines in income inequality (2.8%  $\pm$  1.0%) and poverty rates (9.9%  $\pm$  1.7%) during the boom, although household income increases for the wealthiest and decreases for the poorest. At a systems-level, there is an implied air quality-employment tradeoff of 3 (<1 to 7) job-years created per life-year lost; this tradeoff varies spatially (–1100 to 4400 life-years lost minus job-years created), wherein the job benefit outweighs the air quality costs in most producing counties whereas in all other counties the reverse is true. We also observe temporal inequities, with air quality and employment impacts following the boom-and-bust cycle, while climate impacts are largely borne by future generations. Cross-impact elasticities ( $\varepsilon$ ), which measure the sensitivity between different types of impacts, reveal that employment increases are sensitive to and coupled with increases in air and climate impacts ( $\varepsilon$  = 1.1 and  $\varepsilon$  = 1.3, respectively). The metrics applied here facilitate the evaluation and design of countervailing policies and systems that explicitly account for social inequities mediated through energy infrastructure, supply, and demand. For example, in future energy system transition, such equity metrics can be used to facilitate decisions related to the siting of low-carbon infrastructure

such as transmission lines and wind turbines and the phase-out of fossil fuel infrastructure, as well as to demonstrate changes in distributional tradeoffs such as the decoupling of environmental and employment effects.

## Introduction

The US energy landscape is rapidly evolving with changes over the past decade largely associated with technological advancements enabling dramatic growth in domestic natural gas production. Natural gas now accounts for a third of domestic energy supply and is the largest fuel source for electricity generation. Comprising 20% of the world market, the US is the largest natural gas consumer and producer [1]. Increases in natural gas supply and demand have resulted in impacts to water quality [2–5], air quality [6–9], ecosystems [10, 11], climate [9, 12–14], labor markets [9, 15–17], and public health [18]. The shale gas boom has also presented new technical, social, and political challenges [19]. Despite public concern regarding the distributive and procedural equity of natural gas development [20–24], the literature on the social equity implications of natural gas systems is sparse.

More broadly, in the context of future energy system transitions, there is growing policy and political discourse regarding just transitions and social equity [25]. Common elements of just transitions, which incorporate aspects of climate, energy, and environmental equity and justice, include the distribution of societal costs, risks, and benefits, such as jobs and air pollution, in the transition away from a fossil fuel-dominated system to a low carbon economy [26–29]. Equity is still largely unaccounted for in public and private decision making, and existing analytical tools and processes are inadequate [19, 26, 28, 30, 31]. A systems-level approach that considers embodied energy inequities—the full spectrum of transboundary socio-environmental disparities across the supply chain—may better facilitate decision making [28].

This study develops and demonstrates a systematic approach for quantifying and characterizing the social equity state of an energy system. Here, we focus on the distributional aspects of equity related to natural gas activity across the supply chain from production to end use. We apply this approach to the shale gas boom from 2004 to 2016 in the Appalachian basin, the largest domestic basin with respect to production and reserves [32]. We focus on a single fuel source in a specific region to demonstrate the insight that can be drawn from detailed and data-driven modeling of equity. Many of the results are generalizable to other shale-producing regions, and many of the analytical methods are applicable to other energy system transition contexts.

We assess the distribution of air quality, climate change, and labor market impacts and infrastructure; in addition, we evaluate the intersection of impacts and infrastructure with poverty, income, and race. We select these dimensions of equity based on the academic literature, government reports and proposals, and public discourse related to the shale gas boom and more broadly economy-wide deep decarbonization. We further select these dimensions because they are measurable and each have differing spatial and temporal distributive attributes.

Quantifying diverse dimensions of social equity, which are distributed across varying spatial and temporal scales and variably intersect with income and race, requires employing and developing a suite of empirical and analytical methods and metrics. These methods and metrics are detailed in the supplementary information (SI) available online at [stacks.iop.org/ERL/14/124072/mmedia](https://stacks.iop.org/ERL/14/124072/mmedia). We tailor and evaluate variants of standard equity metrics, such as Gini coefficients, to quantify the spatial and temporal equity of air quality, climate, and employment impacts and infrastructure. We modify the unit-hazard coincidence method to evaluate the spatial coincidence of infrastructure with demographic variables. We also develop several new approaches to quantify the following: job-years created per life-year lost (or premature mortality); air quality mortality risk by race, income, and poverty level; and cross-impact elasticities. We additionally develop regression models to estimate effects of natural gas development on income inequality and poverty. To derive some of the equity metrics, we leverage previously quantified estimates of impacts [9], including premature mortality from primary fine particulate matter (PM<sub>2.5</sub>) and secondary PM<sub>2.5</sub> formed from the atmospheric oxidation of nitrogen oxides (NO<sub>x</sub>) and volatile organic compound emissions, global mean temperature change from carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) emissions, and employment effects associated with natural gas development. In the following sections, we discuss different dimensions of equity, for which we estimate and interpret quantitative metrics, and then, bringing these dimensions together, we develop a collective portrait of the social equity state of the natural gas system in Appalachia.

## Spatial equity of air quality and employment impacts and infrastructure

Spatial equity is the distribution of benefits and costs on the basis of geographic location. Specifically, we

assess the spatial distribution of deaths, jobs, and infrastructure for all segments of the natural gas supply chain and over the development cycle. We apply several standard metrics to quantify spatial inequities, such as the Gini coefficient ( $\eta$ ) and Lorenz curve. The Gini coefficient is an aggregate measure of equity across the system in which each county is compared to all other counties. It ranges in value from 0 for a completely equal distribution to 1 for complete inequity. Lorenz curves depict the proportion of the total impact that is cumulatively borne by a given segment of the population. (See SI for descriptions of additional spatial equity metrics.)

As depicted in figure 1(a), which shows the spatial distribution of cumulative natural gas activity in the Appalachian basin from 2004 to 2016, we observe varying degrees of spatial inequities across the supply chain. Within producing states (Pennsylvania, Ohio, West Virginia), there are high spatial inequities across counties with respect to production ( $\eta = 0.93$ ), with 90% of production concentrated in 10% of counties; this is, in part, dictated by geological constraints of where natural gas is abundant. Moving down the supply chain to end use consumption, which spatially corresponds to more populous regions, we find that there are moderate spatial inequities related to natural gas consumed for electric power generation ( $\eta = 0.68$ ) and commercial, residential, and industrial end use ( $\eta = 0.72$ ). Much of these inequities are persistent over time, given geographically-fixed demand and corresponding power plant, transmission, and distribution infrastructure.

Figure 1(b) shows the spatial equity of air quality impacts from activity across the natural gas supply chain. We find that there are moderate to high spatial inequities of air pollution exposure and associated mortality across counties within producing states ( $\eta = 0.69$ ) and all impacted counties (i.e. counties with mortality  $> 0.1$ ) ( $\eta = 0.77$ ), with 80% of mortalities concentrated in 20% of counties. Spatial air quality inequities have been relatively constant over time, despite the increasing air quality burden resulting from expanding development of natural gas infrastructure within the basin (SI table S2, figure S1).

Similarly, as depicted in figure 1(c), there are moderate to high spatial inequities of cumulative natural-gas-associated employment across counties within producing states ( $\eta = 0.72$ ), with 80% of employment concentrated in 10% of counties. Spatial inequities of employment, which have remained relatively constant over time, are driven by production activities that account for a majority of natural gas-related jobs (SI table S3, figure S2).

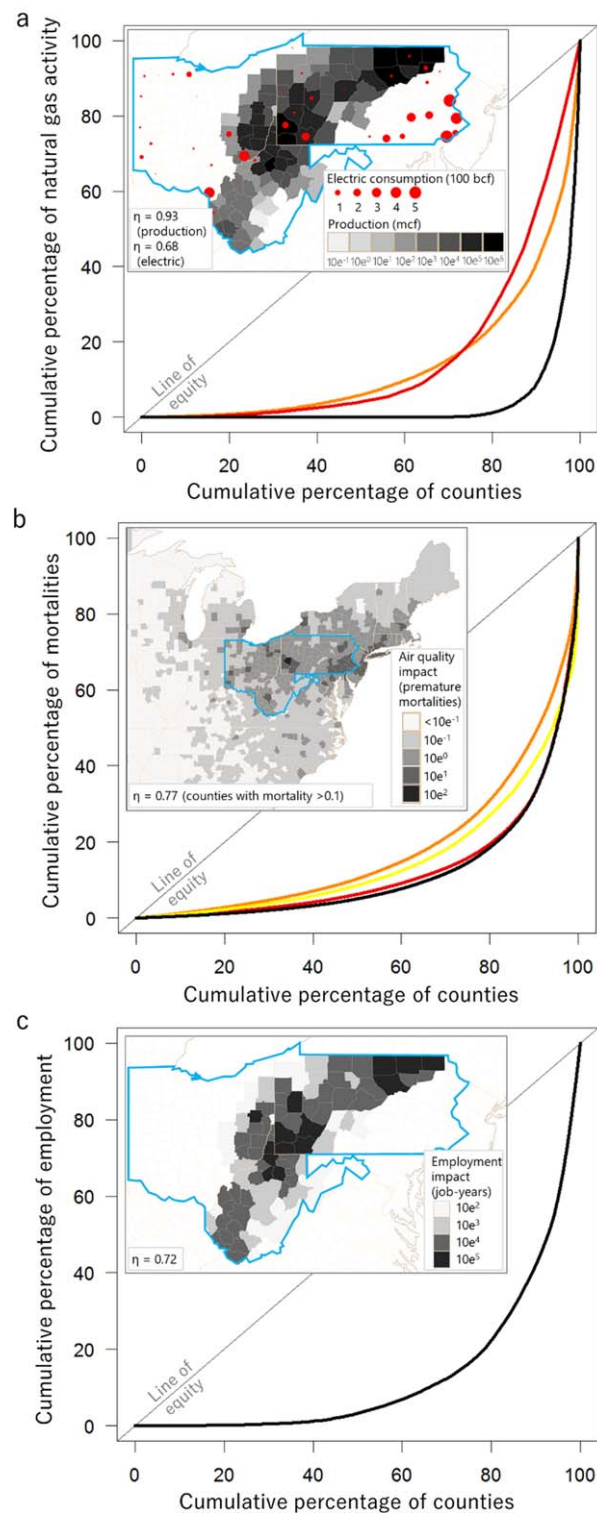
For context, estimated spatial inequities of natural gas activity and impacts exceed that of household income inequality in the US ( $\eta = 0.48$  for 2016) [33]. While spatial inequities can be explained, in part, by geological and end use demand constraints, the siting of infrastructure and the general pattern of

development across the supply chain are also influenced by local economic development decisions and industry learning. Changing patterns of spatial equity over time are additionally affected by the increasing rate of development during the boom, as well as the abundant but ephemeral nature of upstream activity and relatively fixed, longer-term end use activity.

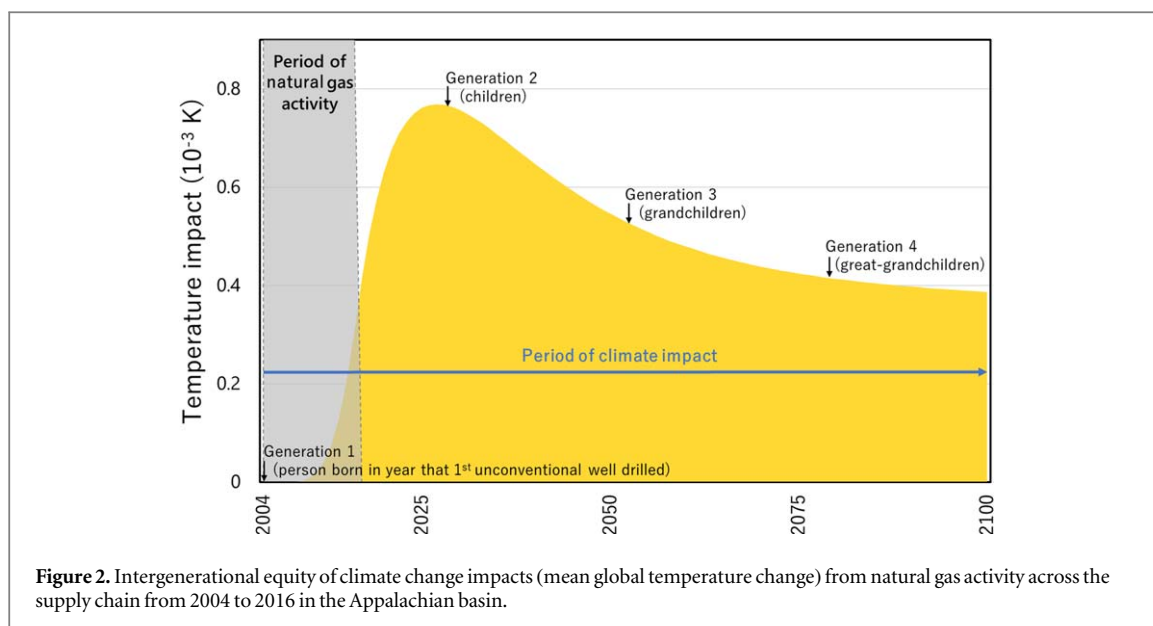
Additional spatial equity metrics, beyond Gini coefficients, are provided in the SI (SI tables S2–3). These additional metrics support the previously discussed trends in spatial equity. These standard equity metrics are useful as aggregate comparative benchmarks of the state of the entire system, and may be used for comparing policies, such as siting and emission standards. However, all of the metrics are limited in their explanatory value of the underlying mechanisms of air quality and employment inequity. This analysis did not consider the spatial equity dimension of climate change impacts, given that we use mean global temperature change as our climate change metric. This metric is useful for characterizing the impact of long-lived greenhouse gases but less suitable for spatially allocating impacts.

## Temporal equity of natural gas development

To evaluate temporal equity—the distribution of benefits and costs over time—we apply a suite of systems-level equity metrics, similar to those used to evaluate spatial equity. The concept of temporal equity is inclusive of intergenerational and intragenerational equity. Relatively short-term air quality and employment impacts track with the natural gas boom-and-bust cycle, whereas climate impacts (in terms of global mean temperature) persist for thousands of years, well beyond the period of natural gas activity [9]. We observe moderate temporal disparities between boom years with respect to air quality-related mortality ( $\eta = 0.47$ ) and employment ( $\eta = 0.44$ ), reflecting the rapid increase in development over that period. With respect to temporal equity of climate impacts, there are high temporal inequities in the near-term (2004–2016) ( $\eta = 0.72$ ), but they decrease over longer time horizons (2004–2100) ( $\eta = 0.23$ ) (SI table S4). This reflects the effects of multiple factors: the rapidly increasing natural gas activity in the near-term, the lagged climate response, the relatively short atmospheric lifetime of  $\text{CH}_4$ , and the persistence of  $\text{CO}_2$  in the atmosphere. For example, the cumulative global temperature impact from the natural gas activity over the next century (2017–2100) is 100 times greater than the cumulative temperature impact over the period of development (2004–2016) (SI figure S3). Figure 2 provides a potentially more salient representation of temporal climate inequities that are not otherwise captured by quantitative equity metrics; we depict an intergenerational framing of climate change impacts,



**Figure 1.** Spatial equity of air quality and employment impacts caused by cumulative activity across the natural gas supply chain in the Appalachian basin from 2004 to 2016. (a) Lorenz curves of the spatial equity of production (black line); commercial, industrial, and residential natural gas consumption (orange line); and electric generation natural gas consumption (red line). Inset: map of production and electric generation natural gas consumption in producing states, which are outlined in blue. Gini coefficients based on counties within producing states, which are outlined in blue. (b) Lorenz curves of the spatial distribution of total (black line), upstream (yellow line), midstream (orange line), and end use (red line) premature mortalities caused by natural gas-related air pollutant emissions in Pennsylvania, Ohio, and West Virginia. Inset: map of total premature mortalities from upstream, midstream, and end use activities. Gini coefficient based on all impacted counties (with mortality > 0.1). Source emission states are outlined in blue. (c) Lorenz curve of the spatial equity of employment from natural gas production (black line). Inset: map of total employment from production. Gini coefficient based on counties within producing states, which are outlined in blue.



**Figure 2.** Intergenerational equity of climate change impacts (mean global temperature change) from natural gas activity across the supply chain from 2004 to 2016 in the Appalachian basin.

whereby we trace the descendants of a child born in 2004, the year in which the first unconventional well was drilled in the Appalachian basin.

Although we use quantitative measures of temporal equity to characterize the state of the system, they are more interpretable when used as comparative measures of different states of the system, such as under different policy interventions. For example, changes in the Gini coefficient can capture the differential effect of marginal  $\text{CH}_4$  emissions abatement that may affect near-term warming rates, as compared to  $\text{CO}_2$  emission reductions through more systemic interventions to transition the energy system away from fossil fuels that result in benefits derived largely by future generations. The Gini coefficient, however, does not capture the effect of reducing  $\text{CH}_4$  emissions as a strategy to avoid or delay reaching ‘tipping points’—irreversible thresholds with drastic consequences—in the climate system [34].

### Equity by race, income, and poverty level

Many studies have found evidence of racial and socioeconomic disparities in the distribution of environmental hazards and locally unwanted land uses [35]. However, they have not considered the impacts of shale gas development. Here, we perform analyses to elucidate the decomposition of impacts and natural gas activity across different subpopulations based on income, race, and poverty levels, which have implications for policy evaluation and decision making in the realm of both environmental justice and local economic development.

#### Equity of air quality impacts by race, income, and poverty level

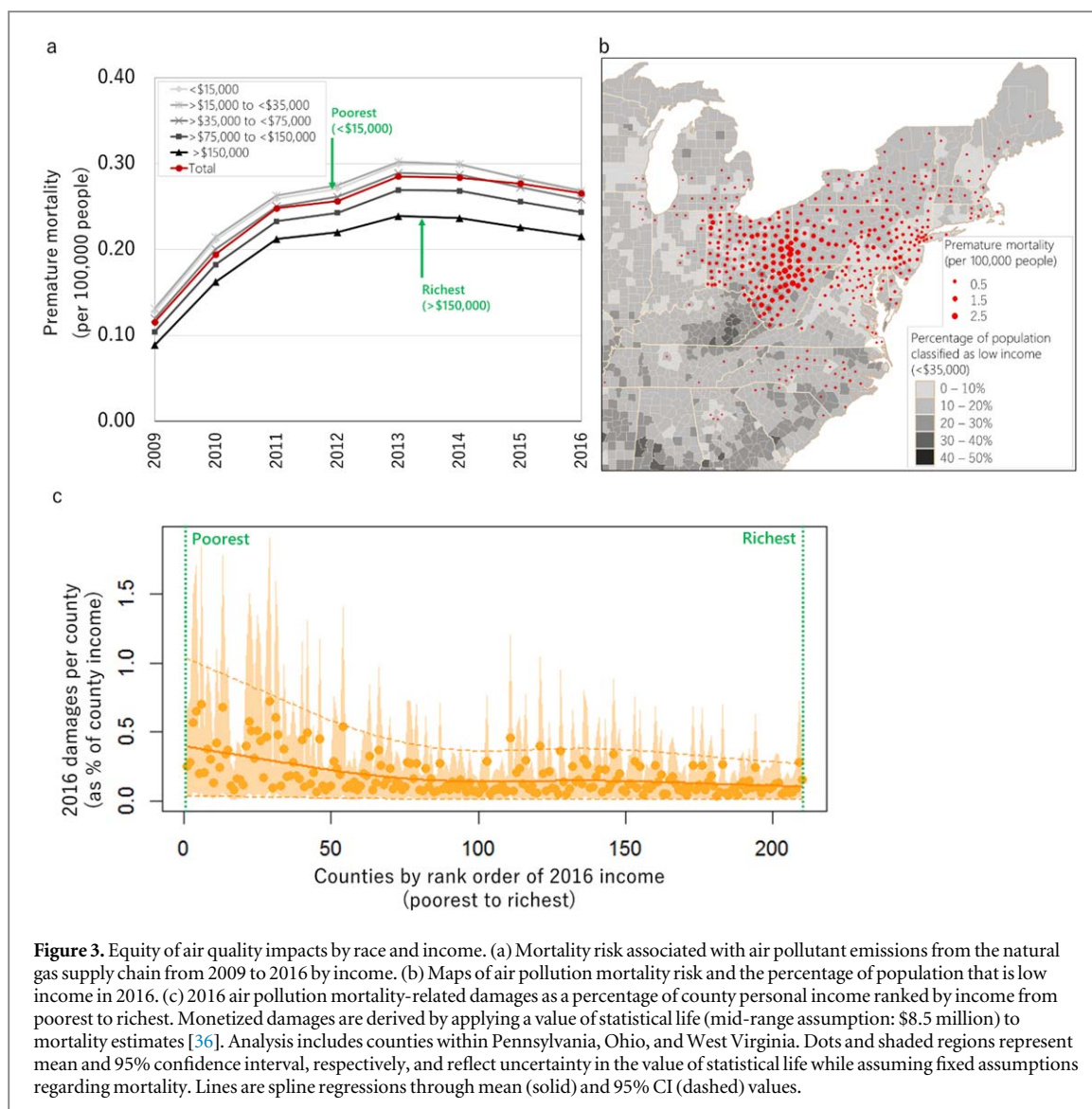
We assess the distribution of air quality-related mortality across subpopulations with respect to race, income, and poverty level. Specifically, we estimate

subpopulation-weighted mortality risk ( $m$ )—the mortality induced by air pollution from natural gas activity from production to end use for each subpopulation relative to the total subpopulation in impacted counties (annual mortality  $> 0.1$ ) (in units of premature mortality per 100 000 people).

With respect to income, we find that air quality impacts are regressive, as shown in figures 3(a) and (b). Mortality risk for the lowest income class ( $< \$15\,000$ ;  $m = 0.22$  in 2016) is higher (18%–31%) than for the highest income class ( $> \$150\,000$ ;  $m = 0.27$  in 2016). We do not, however, observe a difference in mortality risk between populations above and below the poverty line (SI figure S5, table S6). As shown in figure 3(c), we predict a trend of increasing income corresponding to decreasing air quality damages (normalized by income) across counties within Pennsylvania, Ohio, and West Virginia, which further demonstrates the impact of natural-gas related air pollution and associated higher health burden on lower income communities.

We also estimate air quality-related mortality risk by race, accounting for race-based differences in baseline mortality. As shown in SI figure S5, we find that annual mortality risk induced by natural gas activity are higher (47%–52%) for white ( $m = 0.30$  in 2016) than non-white ( $m = 0.16$  in 2016) populations. This is largely a result of the racial composition of rural communities where natural gas development has occurred within the Appalachian basin. Also, in this study we only focus on distributional equity, not recognition and procedural aspects which are additional relevant dimensions of racial inequity.

There are some noteworthy limitations to these findings regarding distributional equity of air quality impacts. The county-level resolution of this analysis will not reveal inequities that occur at finer spatial resolutions. A population-level analysis only demonstrates average effects and not inequities experienced



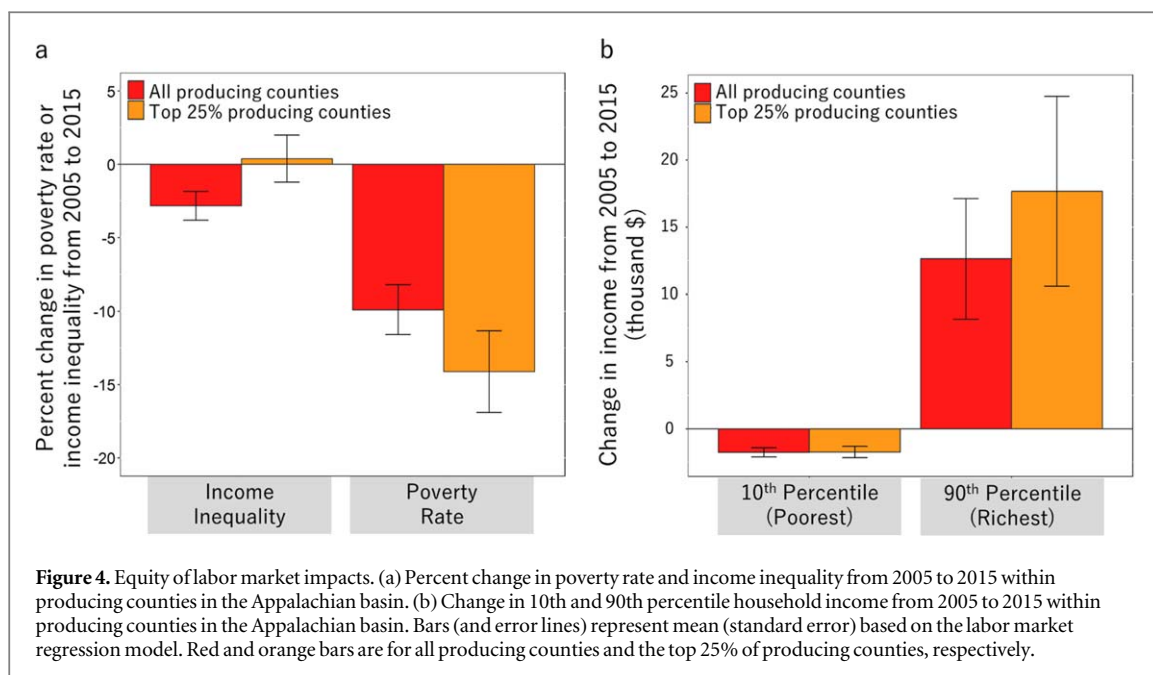
by individual communities. We also only evaluate equity as it relates to premature mortality from  $PM_{2.5}$ , and we would anticipate differing equity implications for other pollutants and health outcomes. Additionally, there are methodological limitations associated with evaluating equity based on health outcomes, such as premature mortality, rather than exposure; this is due to data limitations and a lack of robust evidence in the broader literature regarding differences in baseline mortality risks by race, income, and poverty level and the underlying mechanisms which account for such differences.

### Equity of labor market impacts by income and poverty level

We explore the distributional effects of the natural gas boom on income inequality, poverty rates, and income within local labor markets, using a regression approach to identify changes before and during the boom and between producing and non-producing areas (see SI). Across all counties in the Appalachian region, there have been declines in the income Gini

coefficient—a measure of household income inequality—and increases in the percentage of the population below the poverty line from 2005 to 2015. However, we find statistically significant mean differences between producing and non-producing counties in the change in poverty rates and income inequality, as well as the wealthiest and poorest segments of the income distribution (SI table S7).

Figure 4(a) displays the marginal effects from the natural gas boom on poverty and income inequality measures (SI table S8). To discern the effects associated with different intensities in natural gas activity, we specify two treatment sets—a full treatment set comprised of all 90 producing counties and a treatment set comprised of the top 25% of producing counties. We find that the shale boom is associated with an absolute decline in the percentage below the poverty line of 1.08 (SE  $\pm$  0.26) among all producing counties and 1.72 (SE  $\pm$  0.40) among the top producing counties. This is equivalent to a 9.9% (SE  $\pm$  1.7%) and 14.1% (SE  $\pm$  2.8%) decline in the poverty rates among all and top producing counties,



respectively. Our findings are consistent with several other studies showing that energy booms lower the poverty rate, at least in the short-run [17, 37]. It has further been shown in other studies that poverty rates increase in the long-run during resource declines; as an analog, the 1970s coal mining boom in the Appalachian region decreased poverty, but the 1980s bust reversed this reduction [38].

We additionally find that the shale gas boom is associated with a small, but statistically significant, absolute decline in the income Gini coefficient of 0.01 (SE  $\pm$  0.004) or 2.8% (SE  $\pm$  1.0%), which indicates there has been a decline in income inequality among all producing counties. However, we do not observe a statistically significant change in income inequality among the top producing counties. There is mixed evidence in the labor market literature with respect to the effect of energy booms on income inequality; for example, the recent energy boom in Western Canada generally increased local inequality with a U-shaped growth curve across income distributions [37]. The distribution of the gains from energy booms depends on the skills of local residents and where they fall in the income distribution, the extent of integration between local and regional labor markets, and the extent of spillover [39].

Figure 4(b) shows effects are not equally distributed across the income distribution (SI table S8). For the wealthiest part of the income distribution (90th percentile), we find weakly statistically significant increases in household income (\$12 638 SE  $\pm$  4479) for all producing counties, with a slightly larger effect for the top producing counties (\$17 672 SE  $\pm$  7076); however, there is not a statistically significant increase in the percentage change in income. For the middle of the income distribution (50th percentile), we observe a statistically significant percent

change in income among producing counties of 5.8% (SE  $\pm$  2.5%), but do not find a significant change in the absolute income. For the poorest part of the income distribution (10th percentile), we find statistically significant declines in household income ( $-\$1756$  SE  $\pm$  346) for all producing counties, and for the top producing counties, there is a weakly significant percent increase in income of 10% (SE  $\pm$  5.4%). Based on Security and Exchange Commission filings in 2017 of the top publicly-traded producing firms in the Appalachian basin, the median employee compensation ranged from \$76 000 to \$160 000, further suggesting a more skilled labor force, and there is evidence of vertical inequities within producing firms.

#### Equity of natural gas activity by race, income, and poverty level

We assess racial and socioeconomic disparities in the distribution of natural gas activity and infrastructure, applying standard spatial coincidence methods used in the environmental justice literature. We focus on upstream activity; however, an analogous method can be applied to evaluate disparities in the siting of other infrastructure, such as pipelines and power plants. (See SI.)

We find that there are statistically significant differences between producing and non-producing counties with respect to several demographic variables (SI tables 9 and 10). Assessing the relative importance of demographic characteristics in accounting for these disparities (table S11), we find that from 2010 to 2016, the percentage non-white (odds ratio = 0.93,  $p$ -value  $\leq$  0.00) and the log median household income (odds ratio = 0.005,  $p$ -value  $\leq$  0.00) are statistically significant predictors of the geographic location of production, but the percentage below the poverty line



(odds ratio = 0.96,  $p$ -value  $\leq 0.15$ ) is not. As the non-white percentage decreases or the median household income decreases, there is an increasing probability that a county is producing natural gas. Finer or coarser spatial resolutions of analysis may reveal additional (and potentially counter) correlations. In general, observed disparities based on this spatial coincidence approach may have both environmental justice and local economic development implications, but only if environmental risks or economic benefits are reasonably correlated with the geographic location of production. When benefits or costs are dispersed and are not fully borne by local communities, such as in the transport of air pollutants, a simplistic spatial coincidence approach is limited in its representation of inequity.

### Pairwise air quality, climate change, and labor market tradeoffs

We are interested not only in equity outcomes of individual impacts, as described in previous sections, but also pairwise comparisons of different impacts (e.g. air quality versus jobs) that reveal the implied tradeoffs of natural gas development decisions.

#### Cross-impact elasticity

We estimate cross-impact elasticities ( $\epsilon$ ), which provide information regarding the sensitivity of each impact to changes in other impacts (see SI). At a systems level, based on cumulative impacts across the supply chain over the development period, each pairwise cross-impact elasticity is near unit elastic, which is an intuitive result given that all impacts depend on the intensity of natural gas activity. The employment elasticity of premature mortality ( $\epsilon = 1.1$ ) and cumulative global temperature change over a 100 year integration period ( $\epsilon = 1.3$ ) can be interpreted as: a 1% increase in natural-gas related employment is associated with a 1.1% increase in air quality impacts and a 1.3% increase in climate impacts. Similarly, the premature mortality elasticity of global temperature change over a 100 year integration period ( $\epsilon = 1.2$ ) is slightly elastic, with a 1% increase in air quality impacts corresponding to a 1.2% increase in climate impacts. We would expect that as zero- or low-carbon energy technologies increasingly displace natural gas in the energy system, the employment elasticity of premature mortality and global temperature change would move towards becoming inelastic, with the decoupling of emissions and employment.

#### Air quality and employment tradeoffs

We derive additional metrics to further explore and provide salience to the tradeoff between near-term air quality and employment impacts. This tradeoff varies by supply chain segment, temporally, and spatially,

and is subject to uncertainty with respect to air quality and employment modeling specifications.

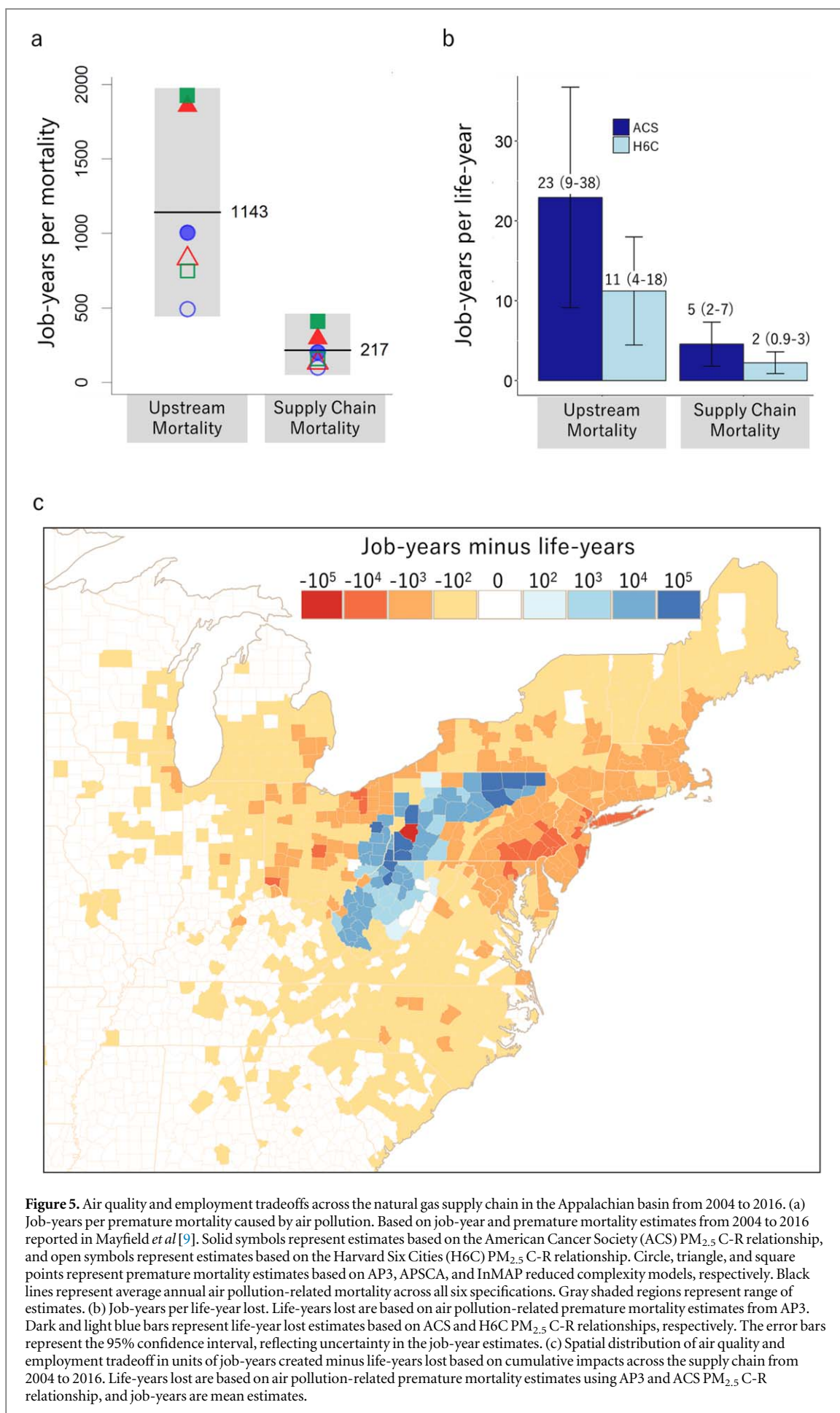
At a systems level, the implied tradeoff, expressed as the ratio of employment and air quality impacts, is 217 job-years per premature mortality, with a range of 100–410 job-years per premature mortality reflecting uncertainty in the air quality model and PM<sub>2.5</sub> concentration-response (C-R) relationship, as depicted in figure 5(a). The mean marginal effect of air pollution on employment, determined by regressing employment versus premature mortality based on annual average estimates, is 157 (95% CI 146–167) job-years per premature mortality (table S13, figures S6–9). Converting premature mortality into life-years lost, the tradeoff can also be expressed as 3 job-years created per life-year lost, with a range from <1 to 7 job-years per life-year reflecting uncertainty in the C-R relationship and employment estimates, as shown in figure 5(b).

Air quality impacts are more spatially dispersed than employment impacts (figure 1), with communities in closest proximity to natural gas infrastructure experiencing the highest mortality risks. The air quality and employment tradeoff varies spatially among producing counties, ranging from 1 to 16 000 job-years per premature mortality [9]. To further explore this spatial tradeoff, as depicted in figure 5(c), we estimate the number of life-years lost minus the number of job-years created by county, finding a range from –1100 to 4400. In most producing counties, more job-years are created than life-years lost, whereas, in all other counties there are more life-years lost than job-years created. This illustrates the misalignment between people holding natural-gas related jobs and those bearing the health effects from air pollution emissions. Most mortalities are within an age range that has largely aged out of the labor market. In addition, jobs within the natural gas sector are held in part by transient workers from outside of the region, whereas the air quality impacts are largely borne by those proximate to natural gas activity.

### Conclusions

A fundamental societal concern is the distribution of benefits and costs across populations, but research is sparse with respect to assessing the multiple dimensions of inequity embodied within an energy system. More specifically, our results extend the literature focused on quantifying environmental and socioeconomic impacts but not distributional effects of natural gas systems [2, 3, 9, 12–18]. We also expand on the existing studies related to the quantification of social equity of energy policies and systems [25] by additionally quantifying inequities related to environmental and labor market impacts and infrastructure, at multiple spatial and temporal scales, and across supply chains.

We focus on the shale gas boom in the Appalachian basin, a major recent transition that has impacted the US



**Figure 5.** Air quality and employment tradeoffs across the natural gas supply chain in the Appalachian basin from 2004 to 2016. (a) Job-years per premature mortality caused by air pollution. Based on job-year and premature mortality estimates from 2004 to 2016 reported in Mayfield *et al* [9]. Solid symbols represent estimates based on the American Cancer Society (ACS) PM<sub>2.5</sub> C-R relationship, and open symbols represent estimates based on the Harvard Six Cities (H6C) PM<sub>2.5</sub> C-R relationship. Circle, triangle, and square points represent premature mortality estimates based on AP3, APSCA, and InMAP reduced complexity models, respectively. Black lines represent average annual air pollution-related mortality across all six specifications. Gray shaded regions represent range of estimates. (b) Job-years per life-year lost. Life-years lost are based on air pollution-related premature mortality estimates from AP3. Dark and light blue bars represent life-year lost estimates based on ACS and H6C PM<sub>2.5</sub> C-R relationships, respectively. The error bars represent the 95% confidence interval, reflecting uncertainty in the job-year estimates. (c) Spatial distribution of air quality and employment tradeoff in units of job-years created minus life-years lost based on cumulative impacts across the supply chain from 2004 to 2016. Life-years lost are based on air pollution-related premature mortality estimates using AP3 and ACS PM<sub>2.5</sub> C-R relationship, and job-years are mean estimates.

and global energy outlook. We find spatial inequities with respect to jobs and air pollution-related deaths. We also show that there are transient temporal inequities with respect to air quality and employment, whereas temporal inequities related to climate impacts are persistent and damages are largely borne by future generations not directly deriving benefits of natural gas extraction and consumption. We also examine multiple impacts, in order to quantify distributional tradeoffs. We find that the implied tradeoff between jobs and air pollution-related deaths is high at a systems level, but variable in space depending on proximity to production and end use activities. There is a disproportionate burden on the poor, with relatively higher mortality risks induced by air pollution from natural gas activity, while the poor also derive fewer benefits. Air and climate costs and employment benefits are also highly coupled within the natural gas system.

The inequities revealed by our analysis underscore the need for developing improved public policies in the Appalachian basin, especially related to disproportionate costs to the poor and to future generations. This study contributes to the procedural equity of the policy process through providing technical information about disparities, and this information can in turn facilitate setting local and state policy agendas. The task remains to design public policy that explicitly addresses inequities mediated through natural gas infrastructure, supply, and consumption. Our analysis suggests the need for embedding equity considerations within policies on the intensive and extensive margins of natural gas supply and consumption, such as well, transmission, and power plant siting standards; greenhouse gas and air pollutant abatement standards; job training and retraining programs; and clean energy mandates. In addition to planning and policy that expressly aims to reduce inequities through modifying physical natural gas system features, policies may also incorporate transfers and compensation. Incorporating equity in policy related to natural gas systems will present many challenges related to policy design, implementation, and enforcement. Specifically, challenges may arise because there is inherent heterogeneity in human-environment-engineered systems; the norm of US policy is to treat equity as a subsidiary objective or ignore it entirely; equity policies derive from potentially divergent ethical judgments; and equity considerations potentially counter private interests and historical opposition.

While our results are specific to the Appalachian basin, some of the conclusions are generalizable to other shale gas basins, although the magnitude and nature of inequities may differ. As the natural gas system continues to evolve, additional inequities will emerge, and the approach and system analytics presented here can be used to assess changes in the equity state of a transitioning energy system. The approach can be expanded to additional spatial and temporal scales, as well as other equity outcomes and impact areas such as energy access, water quality, and ecosystem services. An analogous approach can be applied to and comparisons can be made with other energy sources and technologies, such

as renewables, which may imply vastly different embodied inequities and tradeoffs. Across multiple scales and energy system contexts, the state of social equity differs, given the spatial and temporal heterogeneity in resources, infrastructure, socioeconomics, and values. In general, there are inherent inequities embedded across supply chains, and those bearing the environmental and economic risks largely do not align with those deriving the majority of the benefits.

The shale gas boom also exists within broader regional, national, and global energy transitions related to decarbonization. To meet climate targets such as achieving net zero economy-wide emissions by mid-century, many aspects of the natural gas system will have to fundamentally change. This may entail natural gas production declines, electrification of heating, and retirement and construction of new natural gas generation. These socio-technical transitions have the potential to reduce or relieve persistent inequities across natural gas supply chains, especially as they relate to environmental burdens. The ongoing challenge is to anticipate, identify, and mitigate unknown and emerging environmental and labor market inequities of large-scale transitions.

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## Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Code availability

Sample code developed for the current study are available from the corresponding author on reasonable request.

## Author contributions

ALR secured project funding. ENM, JLC, ALR, and NZM designed the study. ENM acquired and analyzed the data and modeled impacts. ENM, JLC, ALR, and NZM interpreted the results. ENM drafted the manuscript. ENM, JLC, ALR, NZM, and IMLA revised the manuscript.

## Competing interests

JLC serves as the Chair of the Board of Directors of the Center for Responsible Shale Development. The authors declare no other competing interests.

## ORCID iDs

Erin N Mayfield  <https://orcid.org/0000-0001-9843-8905>

Nicholas Z Muller  <https://orcid.org/0000-0003-1712-6526>

Inês M L Azevedo  <https://orcid.org/0000-0002-4755-8656>

Allen L Robinson  <https://orcid.org/0000-0002-1819-083X>

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