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Equity and the environment: An application of the Berliant–Strauss vertical and horizontal equity framework to measuring the distributional effects of air quality regulation

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Abstract

The distributional effects of a major air regulation in the United State in 2015 were analyzed using Berliant and Strauss Index Numbers, a set of theoretical and empirical equity metrics, and reduced-form models that estimate the mortality effects of air pollutant emissions and their source contributions. By viewing the effects of pollution on human mortality as an implicit tax, we found progressivity in 54% to 56% of vertical comparisons and inequity in 92% to 94% of horizontal comparisons. The introduction of the proposed policy made 58% of vertical comparisons more progressive and was equitable to 70% of horizontal comparisons.

KEYWORDS

distributional effect, fine particulate matter, horizontal equity, $PM_{2.5}$, public health effects, vertical equity

JEL CLASSIFICATION

D62; D63; H22; H23; Q52; Q53; Q56

1 | INTRODUCTION

From a social accounting perspective, the analysis of changes in environmental policy is usually divided into three parts: first, ascertaining the effects of such policy changes on different types of environmental pollution (e.g., air, water, land, and so on) and their subsequent impact on human health (usually measured by changes in mortality and/or morbidity) and the natural environment; second, ascertaining the effects of such changes on the allocation of resources or behavioral economic reactions resulting from changes in regulatory, tax, and/or fee environments which implement the environmental policy changes; and third, ascertaining the distributional and/or spatial effects of such environmental policy changes in terms of how various communities across time and space are impacted by such environmental policy changes.

The first analysis is usually the purview of many disciplines in environmental science and epidemiology.

The second analysis is less frequent and performed from an economic perspective. Various kinds of general equilibrium models have been developed by economic or industrial sector; these include contributions from static (or single-period) and dynamic (or multi-period) computable general equilibrium analyses that demonstrate across industrial sectors the direct and indirect effects of policy changes through the public budget on labor, capital, and prices and quantities of other goods and services.[1]

The third analysis is characterized in the environmental science literature as addressing questions of environmental or social justice, and frequently entails showing how various stakeholders, especially those less well off in society, vulnerable populations (e.g., children and the elderly), and/or racial minorities, may be differentially or adversely impacted by pollution.[2] Environmental justice is an important perspective in federal and state rule-making as reflected in, for example, the US Environmental Protection Agency's (2016) guidance on environmental justice and regulatory actions to promote environmental justice in California (California Environmental Protection Agency, 2016).

In principle, all three issues should be analyzed within a complete model of the environment and the economy. However, as a practical matter, both theoretical and empirical analyses typically specialize in examining a subset of these three interrelated effects.

In this paper we focus on the *ex post* or distributional consequences of a particular form of environmental pollution, fine particulate matter ($PM_{2.5}$), and what may be predicted from a federal air regulation that would result in a decrease in $PM_{2.5}$ concentration. We thus abstract from economic behavioral and efficiency issues, *per se*, and seek to evaluate the spatial consequences before and after a proposed environmental policy intervention.[3] Our contribution thus is to reconsider the social accounting that underlies environmental science policy analysis, and to examine the distribution effects of before and after policy intervention through the application of the vertical and horizontal equity framework and set of algebraic index numbers developed by Berliant and Strauss in a number of related papers.[4]

Our paper is organized as follows. Section 2 presents an overview of the background, environmental issues and modeling accomplished to estimate for each county in the USA at 2015 levels the impact of a major reduction in $PM_{2.5}$ pollution by a federal air regulation. Section 3 presents an overview of the vertical and horizontal equity framework and indices developed by Berliant and Strauss in earlier research. It explains how the distribution of county

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[1] For an early contribution of computable general equilibrium modeling, using calibration techniques to solve the various underlying equations, which was applied to the impact of a carbon tax on India's economy, see Ghosh (1990). For an early contribution of computable general equilibrium modeling of the impact of environmental social costs on the US economy through the use of the econometric estimation method, see, for example, Hazilla and Kopp (1990).

[2] See, for example, Rhodes (2005).

[3] This abstraction is based on several considerations. First, there is some evidence (e.g., table 3 in Hazilla and Kopp, 1990) that the social costs of pollution remediation that they studied are empirically modest. Second, we limit our analysis to equity and environmental issues in the interests of tractability and available time and research resources. We hope to examine all three matters through more complex modeling in follow-up research.

[4] See Berliant and Strauss (1983, 1985, 1993, 1996).

by county per capita income and mortality rates by county is analogous to the typical public finance application to characterizing measures of ability to pay of taxpayers in conjunction with a depiction of the effective tax rates due to current tax law and how a change to current law or policy change can be characterized.

Section 4 reviews the underlying data and presents basic economy-wide information about income and mortality rates before and after the simulation of a federal air regulation to control emissions from fossil-fueled power plants. Section 5 presents and then discusses the vertical and horizontal equity analyses of the base case and policy intervention. Section 6 summarizes our findings and discusses further refinement and applications of the suggested methodology in the general domain of environmental policy analysis.[5]

2 | SCIENCE AND POLICY CONTEXT OF FINE PARTICULATE MATTER

Fine particulate matter, inhalable airborne particles of diameter up to 2.5 micrometers, is known to cause cardiovascular and respiratory problems (Krewski *et al.*, 2009; Lepeule *et al.*, 2012). Ambient $PM_{2.5}$ is found to be the most significant environmental health risk factor in the USA (US Burden of Disease Collaborators, 2018) as well as globally (GBD 2017 Risk Factor Collaborators, 2018). The US Environmental Protection Agency's air regulations bring public health benefits, especially by reducing premature deaths from chronic exposure to $PM_{2.5}$, accounting for a majority (over 90%) of monetized benefits (US Environmental Protection Agency's, 2011a; Office of Management and Budget, 2018).

A standard method of estimating such benefits, which is referred as impact pathway analysis, simulates air pollutant emissions, their long-distance transport and complex chemical reactions; quantifies population exposure to ambient air pollutants; and assesses health effects on exposed population. Valuation of the health effects is usually done by a willingness-to-pay analysis. In regulatory analysis, tracking the entire pathway of emissions is usually done by state-of-the-art air quality models, which is computationally expensive.

In order to overcome the high computational costs of employing rigorous air quality models, Heo *et al.* (2016a,b) developed the Estimating Air Pollution Social Impact Using Regression (EASIUR) model to estimate the mortality cost of $PM_{2.5}$ and precursor emissions across the USA computationally efficiently. EASIUR was derived to estimate monetized mortality costs by calibrating regression models to outputs simulated using the Comprehensive Air Quality Model with extensions (CAMx), a state-of-the-art air quality model, for a large set of sample locations across the nation. Heo *et al.* (2017) expanded EASIUR's modeling technique to develop the Air Pollution Social Cost Accounting (APSCA) model that estimates source contributions of $PM_{2.5}$ mortality burdens at a downwind (or receptor) location. The two models closely reproduce the health effects predicted by the computationally rigorous CAMx.

We analyzed, as a case study, the US Environmental Protection Agency's (2011a; 2011b) proposed Cross-State Air Pollution Rule (CSAPR), using EASIUR and APSCA. The CSAPR is a major air regulation that is mandated by the Clean Air Act's "good neighbor" provision. It requires 27 upwind states to reduce emissions from fossil-fuel-powered electric generating units to prevent their substantial interference with maintenance of air quality standards in downwind

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[5] The precise mathematical statements of the Berliant–Strauss family of index numbers may be found in Berliant and Strauss (1983, 1985).

states. We used two 2015 emissions inventories developed for the US Environmental Protection Agency's (2011b) regulatory impact analysis, one for a counterfactual business-as-usual scenario (Base) and the other for a CSAPR scenario (Policy), as input to EASIUR and APSCA to estimate mortality rate due to ambient inorganic $PM_{2.5}$.[6] Compared to the counterfactual scenario, the CSAPR is supposed to reduce $PM_{2.5}$ emissions from power plants by 36% and two gaseous $PM_{2.5}$ precursors, sulfur dioxide (SO_2) and nitrogen oxides (NO_x), by 53% and 36%, respectively. Applying EASIUR and APSCA to Base and Policy scenarios, we analyzed the mortality rates attributable to inorganic $PM_{2.5}$ as shown in Figure 1.

While EASIUR and APSCA enable the construction of spatially distinct health impacts, their estimates do not enable their distributional characterization. Simulated mortality rates are observed to change, but the impact across the distribution of income, which is known to vary spatially, has not been included in these models. The EASIUR and APSCA approaches to environmental modeling can be enhanced by associating each geographic area, which in our empirical implementation below is each US county geographic area, with a measure of ability to pay, county per capita income, which is readily available from the US Department of Commerce Bureau of Economic Analysis (2015).

3 | A PUBLIC ECONOMICS APPROACH TO EXAMINING THE DISTRIBUTIONAL CONSEQUENCES OF $PM_{2.5}$ REDUCTION

Traditionally, distinctions have been made between measuring the vertical and horizontal equity of tax systems based on whether the pre-tax incomes of taxpayers are different (in which case vertical equity is at issue) or similar (in which case horizontal equity is at issue), as well as distinctions between before- and after-tax income that have become more or less equally distributed as a result of a change in tax law. In this section we first review the Berliant–Strauss vertical and horizontal equity framework, and then transition to its application to characterizing the distributional consequences of environmental policy.

The basic contribution is to view environmental health impacts as an implicit community tax because they shorten the lives of community members. The distributional question which then arises is which, among communities, with varying or similar abilities to pay, are impacted, and how to compactly summarize these effects across communities through the use of vertical and horizontal equity index numbers.

3.1 | Classifications of progressivity and horizontal equity

Within statistics and public economics there have been many theoretical and empirical methods proposed to summarize the univariate distribution of income or the multivariate distribution of income and some measure of taxes. A typical measure of taxes is the ratio of net taxes paid to economic income, for example, the average or effective rate of tax. Early contributions to the univariate literature include Atkinson (1970) and Blackorby and Donaldson

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[6] We analyzed the mortality rates attributable to ambient inorganic $PM_{2.5}$ produced by inert primary $PM_{2.5}$, which is emitted directly as $PM_{2.5}$, and secondary inorganic $PM_{2.5}$, which is chemically produced from sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3). EASIUR and APSCA were not yet developed for organic $PM_{2.5}$ precursors, which are emitted mainly by mobile sources.

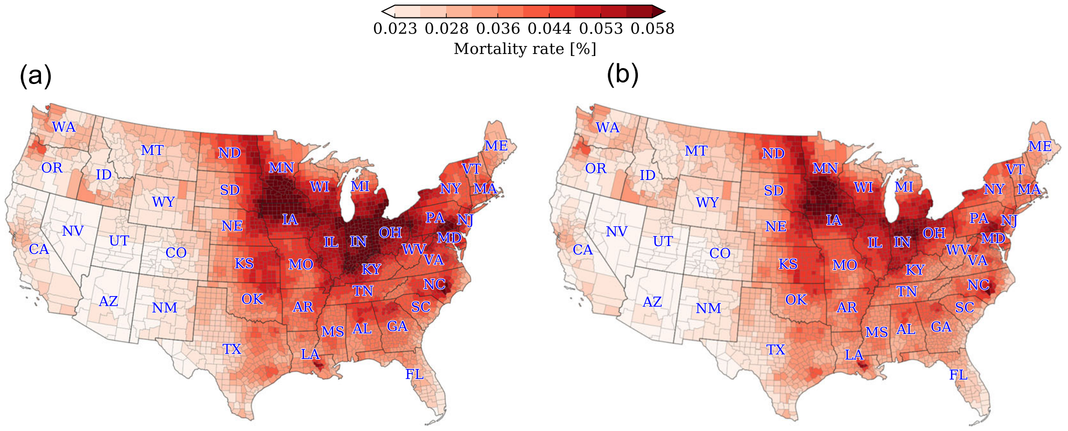

FIGURE 1 Mortality rate attributable to exposure to inorganic $PM_{2.5}$ in 2015: (a) counterfactual scenario, Base case: (b) CSAPR scenario, Policy case [Color figure can be viewed at wileyonlinelibrary.com]

(1978, 1980) who derive univariate index numbers from social welfare functions. Other early contributions such as Kondor (1975), Fields and Fei (1978), Bourguignon (1979), and Shorrocks (1980) find axioms which are consistent with various univariate index numbers.

One branch of the multivariate literature, represented by Berliant and Strauss (1983, 1985, 1993, 1996), proposes and empirically implements index numbers based on relative comparisons of taxpayers in terms of their ability to pay and *effective tax rates*, viewing these index numbers directly as social welfare functions, and fashions the indices with sound axiomatic underpinnings. Berliant and Strauss (1983, 1985, 1993, 1996) follow Wertz (1975, 1978) and partition comparisons between pairs of taxpayers, according to their (unequal) ability to pay (Y) and effective tax rates (t), into three groups: the fraction of pairs of taxpayers for whom a given tax system is progressive, the fraction of pairs of taxpayers for whom a tax system is proportional, and the fraction of pairs of taxpayers for whom a tax system is regressive. As these will be the vertical measures, we consider only pairs of taxpayers who are not "equals" (i.e., $Y_1 \neq Y_2$).

The three vertical measures are constructed so that they sum to 1. Below, when the construction of horizontal index numbers is described, only pairs of taxpayers who are "equals," the remainder, are used (i.e. $Y_1 = Y_2$). To ascertain the *extent* to which taxes are distributed progressively, proportionately, and regressively, Berliant and Strauss (1983) take into account not only the *number* of occurrences of each type of comparison, but also the *degree* of income and effective tax rate disparities. This moves classification from simple counting of comparisons to weighting them by what may be thought of as social welfare weights. The subjective judgment is that it matters when scoring simple comparisons whether taxpayer 1 with an effective tax rate of 20% and taxpayer 2 with an effective tax rate of 15% have similar or very different incomes. This is accomplished by weighting each comparison count by the absolute difference in income of each pair of taxpayers, $|Y_1 - Y_2|$, given $Y_1 \neq Y_2$.

Similar considerations argue for taking into account the *extent* of differences in effective tax rates. That is, it seems to matter, if taxpayer 1 has an income twice that of taxpayer 2, just how similar (or different) the effective tax rates are for the two taxpayers. For example, should taxpayer 1 have an income of $30,000 and taxpayer 2 have an income of $15,000, the "progressiveness" of the tax system would seem to differ if in the first instance the respective effective tax rates were 28% and 20% while in the second instance they were 32% and 18%. Clearly, the former would seem to be *less* progressive than the latter.

To account for such differences in effective tax rates, we weight the comparisons by the *ratio* of effective tax rates, t_1 / t_2, rather than the *differences* in effective tax rates. We use the ratio for several reasons. First, using the ratio differentiates more effectively between a pair of effective tax rates that are close to each other nominally but not relatively. A pair of effective tax rates of 10% and 14% would seem to be much more disparate than a pair of effective tax rates of 46% and 50%. While the *differences* are both 4%, the former pair of tax rates clearly displays more disparity. Second, using the ratio of rates deals with proportional comparisons when forming the weights for each comparison operation. If one were to form a weight based on the difference in effective tax rates, the weight would be zero, while by using the *ratio* the weight becomes unity.

The social welfare weighted vertical index numbers are formed as follows. For each progressive comparison, weight by the difference in incomes times the ratio of effective tax rates, and sum over progressive comparisons. Repeat this procedure for both regressive and proportional comparisons as well. Divide each of these sums by the total weighted sum over all vertical comparisons.

Horizontal equity, unlike vertical equity, does not admit of multiple classifications. Simply put, horizontal equity means either that pairs of taxpayers with equal incomes are treated the same, or not. Counting the number of instances in which $Y_1 = Y_2$ and $t_1 = t_2$ and dividing by the total number of horizontal comparisons yields the fraction of paired comparisons displaying horizontal equity.

By weighting each paired horizontal comparison by the ratio of effective tax rates in order to account for the extent of inequitable treatment by a tax system, the socially weighted equity and socially weighted inequity index numbers are obtained. Notice that each weighted count is divided by the sum over all horizontal comparisons of weighted counts.

In the Berliant–Strauss framework, the weighted horizontal and vertical measures are obtained by making all possible comparisons among pairs of taxpayers, and accumulating the weighted comparisons of each type of classification. Note that the horizontal and vertical measures are quite distinct from each other, and the classification system is exhaustive. Further, in the case of the vertical comparisons, a tax system may be said to have simultaneously progressive, regressive, and proportional components to it. This occurs because comparisons are relative, and the comparisons are numerous. For n individuals in an economy, there are $n(n-1)/2$ total comparisons.

Table 1 displays the classifications of these "static" or single-period vertical and horizontal equity comparisons of pairs of taxpayers, denoted 1 and 2, in terms of their incomes (Y) and effective tax rates (t). The classifications in Table 1 follow Wertz (1975, 1978) and the index scores based on this are described as "without social welfare weights."

TABLE 1 Static Berliant–Strauss vertical and horizontal equity classifications for person pair (1, 2) of income (Y) and effective tax rate (t) without social welfare weights

	Vertical equity	**Horizontal equity**
	$\mathbf{Y_1 > Y_2}$	$\mathbf{Y_1 = Y_2}$
$t_1 > t_2$	Progressive	Inequitable
$t_1 = t_2$	Proportional	Equitable
$t_1 < t_2$	Regressive	Inequitable

TABLE 2 Dynamic Berliant–Strauss vertical and horizontal equity classifications for person pair (1, 2) of income (Y) and effective tax rate (t) between policy A and policy B

	Dynamic Vertical Comparison		
Static Vertical Comparison	**More Progressive**	**No Change**	**More Regressive**
Progressive $Y_1 > Y_2, t_1^A > t_2^A$	$\frac{t_1^B}{t_1^A} > \frac{t_2^B}{t_2^A}$	$\frac{t_1^B}{t_1^A} = \frac{t_2^B}{t_2^A}$	$\frac{t_1^B}{t_1^A} < \frac{t_2^B}{t_2^A}$
Proportional $Y_1 \neq Y_2, t_1^A = t_2^A$	$t_1^B < t_2^B$ for $Y_1 < Y_2$	$\frac{t_1^B}{t_1^A} = \frac{t_2^B}{t_2^A}$	$t_1^B < t_2^B$ for $Y_1 > Y_2$
Regressive $Y_1 < Y_2, t_1^A > t_2^A$	$\frac{t_1^B}{t_1^A} < \frac{t_2^B}{t_2^A}$	$\frac{t_1^B}{t_1^A} = \frac{t_2^B}{t_2^A}$	$\frac{t_1^B}{t_1^A} > \frac{t_2^B}{t_2^A}$

	Dynamic Horizontal Comparison	
Static Horizontal Comparison	**Equitable**	**Inequitable**
Equitable $Y_1 = Y_2, t_1^A = t_2^A$	$\frac{t_1^B}{t_1^A} = \frac{t_2^B}{t_2^A}$	$\frac{t_1^B}{t_1^A} \neq \frac{t_2^B}{t_2^A}$
Inequitable $Y_1 = Y_2, t_1^A \neq t_2^A$	$\frac{t_1^B}{t_1^A} = \frac{t_2^B}{t_2^A}$	$\frac{t_1^B}{t_1^A} \neq \frac{t_2^B}{t_2^A}$

The framework in Table 1 may be extended to comparing an initial and proposed tax regime (A and B), which leads to "dynamic" index numbers. Such measurement, in the absence of complex modeling of the indirect effects of the new tax system on income, presumes that economic income is independent of which tax system, A or B, is imposed. Table 2 provides a summary of the classifications of the Berliant–Strauss "dynamic" index numbers; "dynamic" means equity classification and comparisons of taxpayers 1 and 2, with incomes Y_1 and Y_2, across initial and subsequent tax regimes, A and B. Given an initial classification of ability to pay for two taxpayers, by comparing the own ratio of effective tax rates of tax regime B to tax regime A, one may exhaustively define whether tax system B is *more* progressive than tax system A for all pairs of taxpayer comparisons. Note that these dynamic vertical comparisons sum to 1, and that the same analysis can be accomplished for horizontal comparisons.

3.2 | Moving from pairs of individual income effective tax rates to pairs of community mortality rates

Application of the vertical and horizontal equity framework in Section 3.1 to the characterization of equity and the environment is straightforward and, we think, quite intuitive. Comparisons are now among pairs of homogeneous individuals in groups 1 and 2; each group of individuals constitutes a "community." At a moment in time, these communities vary across space in terms of their ability to pay, Y, and the impact of the environment on community members' longevity. Communities exist across the entirety of a nation's geography, so that each member of society resides in only one community. Each community's rate of loss of lives due to environmental factors constitutes an implicit tax rate which we denote by m. Without more detailed information about the actual income of an individual within a community whose loss of life is due to $PM_{2.5}$, say, we attribute that lost life, as a first approximation, to the mean community income or per capita income. In so doing, we choose to use average income data for 2015, which is complete across the USA, rather than age-specific income levels which are available only for limited US geographies.[7] The dollar value of the loss of a life, which is empirically below in terms of the value of a statistical life (Viscusi, 2010), can be thought of as the mortality rate in 2015 in the community times representative or mean community income in 2015.[8]

Unlike some other social justice approaches from the environmental science literature, we focus our social accounting framework in terms of one period, and do not seek to calculate the subsequent effects of a reduction in mortality rates on the surviving group members a period later. To do so would entail ultimately panel or time-dependent information about the duration of improved health status of each person, and the level and composition of their income (market vs. retirement), and ultimately raises Markov modeling issues which could become speculative, and possibly prone to error. Also, doing such time-dependent analysis raises difficult questions of what social discount rate should be employed, as well as issues in predicting the *growth* in Y and changes in m over time due to improvements in non-environmental health interventions.

The transition from population-weighted counts to those utilizing both population counts and social welfare weights in the analysis of vertical and horizontal equity effects of the impact of a change in environmental policy completes our new framework. Thus, we inquire how much our inferences about the vertical and horizontal equity of environmental policy might vary when we account for absolute differences in pairs of communities' ability to pay and ratios of mortality rates. Moreover, this can be done in terms of performing the classifications for environmental policy regimes, A and then B, two static sets of comparisons, or keeping track of the transition from A and B for all community and mortality rate pairs.

4 | EMPIRICAL METHODOLOGY AND DATA

As already discussed, we compare mortality rates in 2015 in a counterfactual (or baseline) emissions scenario to simulated mortality rates in the US Environmental Protection Agency's CSAPR scenario for all 3,109 counties in the continental USA (see Figure 1). Per capita income of each county is due to the Regional Economic Information System (US Department of Commerce Bureau of Economic Analysis, 2015), and is composed of wages, proprietors' income, dividends, interest, rents, and government benefits (see Figure 2).

In 2015, the observed mean baseline mortality rate due to inorganic $PM_{2.5}$ was 0.058% and is simulated to decline to a mean mortality rate of 0.052%.[9] About 11,400 lives are projected to be saved at 2015 levels were the CSAPR to take instantaneous effect. With an overall mean per capita income of \$48,555 and 11,400 lives saved, the monetary value of lives saved due to CSAPR in 2015 is about \$550 million.

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[7] The US Census Bureau stopped measuring money income at the small-area level in 2000.

[8] For a balanced discussion of the effects of heterogeneity of income and age when constructing the value of a statistical life, see, for example, Viscusi (2010). In this paper, because we have complete spatial information about $PM_{2.5}$ effects, we must use per-capita income as our measure of ability to pay because income by type (market vs. retirement) × age groupings do not exist for the simulation year. We plan to explore more limited spatial pollution data which can be linked to income by type by age groupings.

[9] These rates are weighted by county adult population (aged 30 and over) in 2015, which numbered 190.7 million.

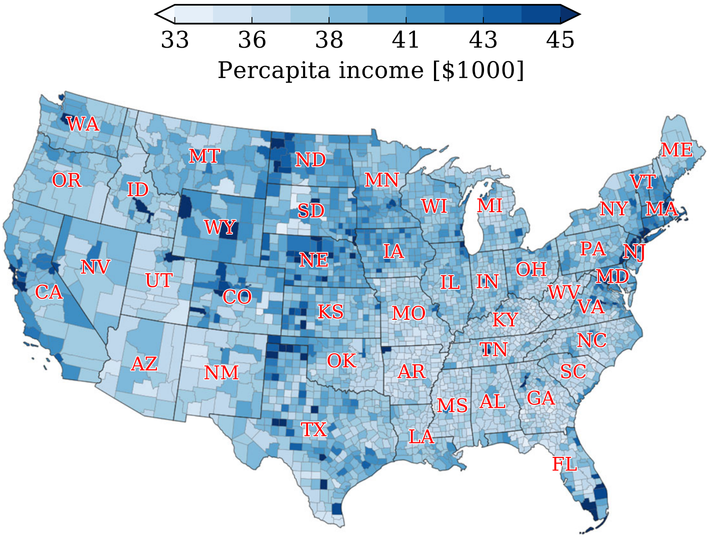

FIGURE 2 Per capita income in 2015 [Color figure can be viewed at wileyonlinelibrary.com]

The data for the Bureau of Economic Analysis per capita income and baseline mortality rates were partitioned into a 25 × 25 matrix using adult population in 2015 as the weight to distribute per capita income and to distribute the baseline mortality rates. Thus there were potentially 625 per capita income × mortality rate cells to compare to each other, or $(25\times 24)/2=300$ comparisons. Figure 3 displays the mean baseline and policy mortality rates across the cumulative population of US counties, and also the mean county per capita income across the cumulative, adult populations of US counties.

5 | EMPIRICAL RESULTS AND DISCUSSION

We now turn to our vertical and horizontal index number analysis of 2015 baseline and policy impacted mortality rates across income of the 3,109 counties in the continental USA. We use

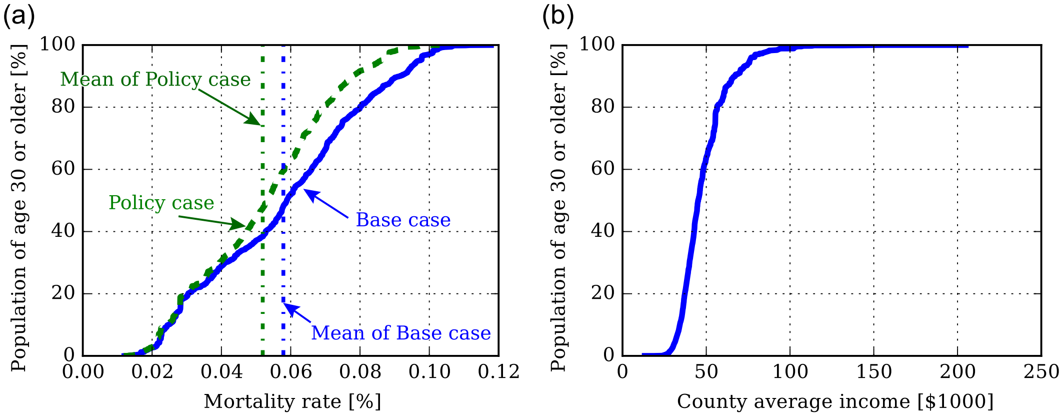

FIGURE 3 Mortality rate and average county per capita income in 2015 across all the counties the in USA. (a) Cumulative distribution of mortality rate (m) over population aged 30 and over due to inorganic $PM_{2.5}$, (b) Cumulative distribution of Bureau of Economic Analysis county per capita income over population aged 30 and over. Mean values of per capita income are adult population weighted [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Static Berliant–Strauss vertical and horizontal equity index numbers of 2015 counterfactual (or Base) and Cross-State Air Pollution Rule (or Policy) scenarios

	No *P* & No *W*		*P* & No *W*		No *P* & *W*		*P* & *W*	
Weighting schemes	**Base**	**Policy**	**Base**	**Policy**	**Base**	**Policy**	**Base**	**Policy**
Vertical equity								
% Comparisons progressive	51.2%	53.2%	51.1%	52.0%	49.1%	52.5%	54.1%	56.1%
% Comparisons proportional	4.0%	4.7%	3.7%	4.6%	2.2%	2.6%	2.0%	2.4%
% Comparisons regressive	44.8%	42.2%	45.1%	43.5%	48.7%	44.8%	43.8%	41.5%
Horizontal equity								
% Comparisons equitable	4.4%	5.5%	11.3%	12.6%	2.6%	3.4%	6.4%	7.6%
% Comparisons inequitable	95.6%	94.5%	88.7%	87.4%	97.4%	96.6%	93.6%	92.4%

Note: *P* indicates population-weighted indices and *W* indicates welfare-weighted indices.

four weighting schemes which reflect not weighting or weighting equity comparisons by the adult population (No *P* or *P*), and weighting or not weighting equity comparisons by the difference in welfare (No *W* or *W*) (that is, $|Y_i - Y_j| \cdot \max(m_i/m_j, m_j/m_i)\ i \neq j$). Table 3 contains the single-period calculations using four different weighting schemes for the comparisons.

Given our initial partition of county per capita income and mortality rates, we find that the application of the CSAPR raises slightly the fraction of progressive comparisons. Simply counting comparisons as the weighting scheme (No *P* and No *W*), we see that baseline mortality rates were progressively distributed in 51.2% of the comparisons; we also found that 44.8% of the vertical comparisons were regressively distributed. Weighting by the adult age population (*P* weights) and taking into account differences in welfare (*W* weights), our preferred measure, raises the percentage of progressive comparisons from 54.1% to 56.1%. Again focusing on our preferred weight scheme, we see that this improvement in vertical progressivity is accomplished by a corresponding decrease in vertical regressivity from 43.8% of the comparisons to 41.5% of the comparisons as a result of the application of the CSAPR.

Perhaps surprising is that we find that the *horizontal* comparisons display very high levels of horizontal inequity (i.e., $m_i \neq m_j$) given $Y_i = Y_j$; for our preferred weighting scheme (*P* and *W*), the baseline analysis of communities whose per capita incomes are quite similar indicates that over 93.6% of the comparisons display horizontal inequity, and application of the CSAPR reduces the weighted number of horizontal inequity comparisons to 92.4%. Thus, our single-period analysis indicates that application of the CSAPR improves vertical progressivity, reduces vertical regressivity, and reduces horizontal inequity; however, these *changes* are relatively modest.[10]

Table 4 displays the results of keeping track of the origin and destination of mortality rates through the use of dynamic Berliant–Strauss vertical and horizontal equity index numbers. There are two main effects of such housekeeping. First, our inferences about how much *more* the classifications change when percapita incomes are similar (dynamic horizontal comparisons) is now quite sensitive to the weighting scheme employed. That is, compare the *P* and *W* weighted results for policy in Table 3 to those in Table 4. Second, we find that keeping track of

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[10] The finding of high levels of both horizontal inequity and vertical progressivity in our analysis of the distributional effects of $PM_{2.5}$ pollution is consistent with the earlier analyses of the federal individual income tax reported by Berliant and Strauss in several papers, for example, Berliant and Strauss (1993). That higher per capita income areas have higher mortality rates due to $PM_{2.5}$ pollution may reflect not only greater population density, but also higher consumption of goods which are polluting, that is, automobiles, electricity fueled by carbon sources which generate relatively higher $PM_{2.5}$ pollution, etc. It follows that relatively greater *reductions* in such areas' $PM_{2.5}$ levels due to a simulated policy change would be regressively distributed, and demonstrates the insights which decomposing the nature of an externality into its spatial, horizontal, and vertical components can accomplish.

TABLE 4 Dynamic Berliant–Strauss equity index numbers of Cross-State Air Pollution Rule

Weighting schemes	No P & No W	P & No W	No P & W	P & W
Vertical equity				
% Comparisons more progressive	59.6%	55.1%	65.6%	58.3%
% Comparisons no change	3.9%	3.7%	3.4%	3.3%
% Comparisons more regressive	36.4%	41.2%	31.1%	38.4%
Horizontal equity				
% Comparisons equitable	9.6%	71.1%	9.0%	69.9%
% Comparisons inequitable	90.4%	28.9%	91.0%	30.1%

Note: P indicates population-weighted indices and W indicates welfare-weighted indices.

the *relative* mortality rates before and after application of the CSAPR, using our preferred weighting scheme (P and W), makes relative comparisons more progressive more frequently (58.3%), and more regressive less often (38.4%). On the other hand, horizontal *inequity* becomes relatively less frequent as the dynamic analysis also shows that application of the CSAPR finds relative, horizontal inequity to be 30.1% while the static horizontal inequity analysis in Table 3 finds 92% of horizontal comparisons inequitable.

6 | SUMMARY AND PROSPECTS

Our aim in this paper has been to reconsider the social accounting used to make inferences about the distributional consequences of environmental policy, and in particular to examine how improvements in human longevity or lowered mortality rates through reductions in $PM_{2.5}$ impact communities of varying abilities to pay. A class of vertical and horizontal equity index numbers due to Berliant and Strauss is implemented to examine how 3,109 US counties in 2015 with very similar per capita incomes and counties with very different per capita incomes might fare.

With regard to results from comparing counties with similar or nearly equal per capita incomes, we find that baseline mortality rates and those reflecting the simulated imposition of the US Environmental Protection Agency's Cross-State Air Pollution Rule vary substantially. Horizontal inequity is slightly reduced from 93.6% to 92.4% of the paired comparisons. With regard to baseline mortality rates and those resulting from simulated imposition of the CSAPR, we find that between 54.1% and 56.1% of the comparisons of mortality rates display *progressivity* in single-period comparisons, while 58.3% display *more* progressivity when keeping track of initial and subsequent mortality rates by per capita income class. Also, we find that *regressivity* in the relationship between per capita income and mortality rates falls from 43.8% of the comparisons to 41.5% of the comparisons after simulation of the effects of the CSAPR.

Finally, we note that our analysis enables the systematic consideration of the extent as well as the magnitude of the effects of environmental regulations (i.e., affecting a large portion of the population across a large region). Our metrics that characterize or intuitively summarize the distributional effects of environmental regulations allow direct comparisons of policy alternatives, thus improving the regulatory transparency. While there have been some efforts to employ a univariate metric such as the Atkinson index (Levy *et al.*, 2006), the US Environmental Protection Agency (2010, 2016) does not recommend such univariate metrics. The US Environmental Protection Agency observes that some of the commonly used univariate measures (e.g., the Gini coefficient, Atkinson index, and Kolm index) are neither tested nor clearly relevant to be useful in regulatory analysis. In this context, this paper shows that the Berliant–Strauss multivariate, vertical and horizontal index numbers can provide more useful metrics in the environmental policy research arena.

Whether our empirical results are robust depends on further empirical research. Three avenues suggest themselves. First, there is merit in trying to adjust per capita incomes for differential cost of living as well as by age. Unfortunately, there currently is no county by county general cost of living index for each of the 3,109 counties in the USA, and income × age data at the county level is no longer available for all geographic areas; however, it may be possible to standardize at least for differential living costs proxied for by rental or housing sales prices at a moment in time when measured on a per square foot basis. Should small-area data on income × age become generally available, or at least for areas differentially impacted by pollution, there is merit in exploiting such distributional information in conjunction with small-area data on mortality by age.

Second, as noted above, there is merit in connecting our distributional analysis to computable general equilibrium models at the county level which account for not only industry detail, but also income distribution or broad-based consumption detail.

Finally, exploration of international cross-sections in terms of time and/or spatial resolution of mortality and income data can inform in part whether the progressive, regressive, and horizontal inequity patterns we have captured here are observed elsewhere.

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