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Human Health and Economic Impacts of Ozone Reductions by Income Group

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Human Health and Economic Impacts of Ozone Reductions by Income Group

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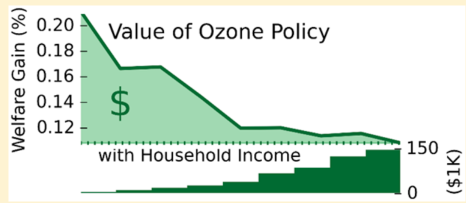
Supporting Information

ABSTRACT: Low-income households may be disproportionately affected by ozone pollution and ozone policy. We quantify how three factors affect the relative benefits of ozone policies with household income: (1) unequal ozone reductions; (2) policy delay; and (3) economic valuation methods. We model ozone concentrations under baseline and policy conditions across the full continental United States to estimate the distribution of ozone-related health impacts across nine income groups. We enhance an economic model to include these impacts across household income categories, and present its first application to evaluate the benefits of ozone reductions for low-income households. We find that mortality incidence rates decrease with increasing income. Modeled ozone levels yield a median of 11 deaths per 100 000 people in 2005. Proposed policy reduces these rates by 13%. Ozone reductions are highest among low-income households, which increases their relative welfare gains by up to 4% and decreases them for the rich by up to 8%. The median value of reductions in 2015 is either $30 billion (in 2006 U.S. dollars) or $1 billion if reduced mortality risks are valued with willingness-to-pay or as income from increased life expectancy. Ozone reductions were relatively twice as beneficial for the lowest- compared to the highest-income households. The valuation approach affected benefits more than a policy delay or differential ozone reductions with income.



■ INTRODUCTION

Tropospheric ozone is a harmful pollutant that affects human health and economic welfare. Ozone concentrations and the effects of control policies can vary with household income. Previous studies of the future impacts of U.S. air pollution policy have either included ozone but have not systematically evaluated impacts by income group[1−6] or have not included ozone.[7] Here, we enhance an integrated modeling framework to assess the differential health and economic impacts of ozone reductions across household income categories.

U.S. studies find low-income households can be more[8,9] or less[9−12] exposed to ozone. These studies each examine a different subset of the U.S. population (e.g., living near ambient monitors) or regions (e.g., Phoenix, AZ) and use two to five categories of income (e.g., below or above $50 000).

Policies that reduce ozone can have differential effects on ozone with income. Bento, Freedman, and Lang[13] suggest the 1990 Clean Air Act (CAA) Amendments reduced more ozone among low-income households and were twice as valuable for the poor. Several recent ozone policies, including the Cross-State Air Pollution Rule (CSAPR) that was meant to replace the Clean Air Interstate Rule (CAIR) after 2005 and the reduction of the National Ambient Air Quality Standard recommended in 2008, have been delayed through judicial or administrative actions.[14−16]

Though retrospective studies find that ozone concentrations and policy impacts can vary with income, prospective policy analysis remains limited. Previous analyses of air quality policy assessed unequal risks from fine particulate matter and poverty[17] and impacts to the poor.[6] Empirical evidence suggests that income affects economic preferences for avoiding health risks from pollution.[18−21] Current U.S. regulatory practice applies the same valuations for marginal health risks across income groups and does not evaluate effects with income.[22]

One complementary approach to traditional regulatory analysis is computable general equilibrium (CGE) economic modeling. CGE modeling solves prices to equate supply and demand across markets to study the long-run dynamics of policy. An advantage of CGE is its potential to assess the relative value of policies by income group given pre-existing interacting policies, resource allocations, and price responses.[23] Empirical evidence shows general equilibrium effects alter the benefits of ozone reductions,[24−26] as do the cumulative benefits of improved health over time, which are captured in CGE modeling.[2] The Environmental Protection Agency (EPA) Second Prospective Report on CAA amendments[7] included CGE modeling to estimate impacts across four household income categories but did not include ozone-related mortality. Others have included ozone-related mortality in CGE estimates

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Table 1. Health Impact Functions and Valuations

end point−end point group	ages (years)	individual studies	pooling	valuation (2006 U.S. dollars)
premature mortality	0−99	Ito et al. (2005)[61]	equal weight pooling of all studies	$8 000 000
		Schwartz (2005)[62]		
		Bell et al. (2004)[63]		
		Bell et al. (2005)[64]		
		Levy et al. (2005)[65]		
		Huang et al. (2005)[66]		
respiratory hospital admissions	>65	Schwartz (1995)[67]—ICD[b] 460−519 (all respiratory)	random effects pooling of outcomes from four cities: Tacoma, New Haven, Detroit, and Minneapolis	$28 000
		Schwartz (1994);[68] (1994)[69]—ICD 480−486 (pneumonia)		
		Moolgavkar et al. (1997)[70]—ICD 480−487, 490−496 (pneumonia, COPD)		
		Schwartz (1994)[69]—ICD 491−492, 494−496 (COPD)[c]		
	<2	Burnett et al. (2001)[71]	N/A	$10 000
asthma-related ER[a] visits	5−34	Jaffe et al. (2003)[72]	random and fixed effects pooling of all three studies	$370
	all ages	Peel et al. (2005)[73]		
		Wilson et al. (2005)[74]		
minor restricted-activity days	18−64	Ostro and Rothschild (1989)[75]	N/A	$60
school loss days	5−17	Gilliland et al. (2001)[76]	random and fixed effects pooling of both studies	$90
		Chen et al. (2000)[77]		

[a]ER: emergency room. [b]ICD: International Statistical Classification of Disease. [c]COPD: chronic obstructive pulmonary disease.

of pollution impacts but did not examine effects by income group.[1−3,5,27]

Here, we conduct a modeling experiment to examine the relative importance of U.S. ozone reduction policies for low-income households and to explore the importance of policy delays, unequal ozone levels, and methodological choices on this result. We include the entire continental U.S. to model ozone concentrations across nine household income categories. We then model changes in ozone concentrations across household income categories using a scenario evaluated by the U.S. EPA for the Cross-State Air Pollution Rule composed of policies planned for 2014.[28] We employ a framework, elaborated elsewhere,[29,30] that connects a regional chemical transport model (the Comprehensive Air Quality model with extensions, CAMx) and a health impacts model (Benefits Mapping and Analysis System (BenMAP)) with a CGE model of the U.S. energy and economic system (U.S. Regional Energy Policy model, USREP)). We extend this framework here to examine the health and economic effects of ozone concentrations and ozone reductions with income.

■ MATERIALS AND METHODS

We model ozone concentrations as well as ozone reductions and their resulting economic impacts using an integrated assessment framework that links an advanced air quality modeling system to an economic model capable of analyzing impacts across income groups. This section describes our methods for modeling health and economic impacts across income groups and their application to ozone concentrations and reductions.

Health Outcomes and Valuations. We use CAMx version 5.3 to model hourly ozone concentrations on a 36 km grid of the continental U.S. with 2005 emissions and meteorology (see the Supporting Information). For the policy scenarios, we use 2005 meteorology and 2014 emissions processed with the Sparse Matrix Operating Kernel Emissions model (SMOKE) version 2.6.[31]

We calculate mortality and morbidity associated with changes in ozone concentrations using BenMAP v4.0 following the U.S. EPA.[6] Table 1 lists the end points and concentration−response functions applied. To estimate 95th confidence intervals, we used 1000 Monte Carlo simulations of the distributions of concentration−response functions in Table 1. We assign resulting estimates to household income groups based on the proportion of households in each income group in each region of USREP, which is in turn based on census data.[32]

U.S. Regional Energy Policy Model. *2.1. USREP Model Description.* USREP is a recursive dynamic CGE economic model designed to explore environmental impacts of environmental and energy policy across nine income groups. USREP is a full employment model in which utility-maximizing consumers supply four factors of production (labor, capital, land, and resources) to profit-maximizing firms in 12 regions. It calculates commodity prices that support equilibrium between supply and demand in all markets from a base year of 2006 with 5 year time-steps to assess the long-run dynamic effects of policy on resource allocation and income distribution. USREP has been described previously, including: tests of its structure, inputs, and assumptions; model intercomparisons; economic and distributional impacts (across economic sectors, regions, and income groups) of climate change and energy policies; and economy-wide impacts of ozone and fine particulate matter.[23,29,30,32−36] USREP's economic structure, 12 geographic regions, and underlying data are described in the Supporting Information.

We estimate the effect of policies on consumer welfare composed of consumption (capturing market-based activities) and leisure (capturing nonworking time).[37] We present the change in consumer welfare as the equivalent variation, i.e., the income amount that consumers would pay to avert the price

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effects of a policy; here, they are due to health-related impacts from changes in ambient ozone concentrations.

2.2. Pollution Health Services Sector in USREP. We add the health impacts by income group related to changes in ozone concentration to USREP's pollution health services sector (described in detail by Saari et al., 2015).[30] A schematic depicting this sector and its input from CAMx and BenMAP is in the Supporting Information. This sector accounts for morbidities and mortalities through lost wages, lost leisure, and medical expenses that vary with pollution levels. It draws input from the services sector and from the household labor supply. It affects consumer welfare through private consumption and leisure.

Assessing Ozone Exposure and Impacts by Income Group under Planned Reductions. For our modeling experiment, we analyze a policy scenario that reduces ozone concentrations that the EPA developed to evaluate the CSAPR.[28] This hypothetical 2014 scenario includes CSAPR and other policies and plant closures detailed by the EPA that apply to the electricity sector and beyond.[28] CSAPR was meant to replace CAIR after 2005 and had reduction deadlines of 2012 and 2014; however, the rule was overturned by a DC Circuit Court of Appeals in 2012.[15] Following several judicial actions, compliance with Phase I emissions budgets is now required in 2015 and 2016. The policy scenario is composed of ozone reductions that were planned for 2014 starting from 2005 and which vary across income groups and regions. We implement the ozone reductions as a linear interpolation between 2005 and 2014. In the base case scenario, we assume that no ozone reductions occur and that ozone concentrations remain constant at 2005 levels. We evaluate only the benefits of these policies with respect to the base case and do not account for the policy costs. The policy benefits are accrued through reducing ozone-related health risks, which decreases the resources demanded by the Pollution Health Services Sector and increases consumer welfare as described above.

We also analyze two sensitivity scenarios. First, we delay implementation by 11 years. Next, we equalize ozone reductions with income by applying the regional average ozone for all income groups. We use this to develop a sensitivity scenario that assigns the average change in health outcomes under the policy scenario in 2014 to all households within a region. Thus, our four scenarios are (1) BASE05, constant 2005 ozone levels; (2) POLICY14, ozone reductions implemented between 2005 and 2014; (3) POLICY25, ozone reductions implemented between 2015 and 2025; and (4) EQUALO3, all households in a region have the same ozone reductions.

Valuation of Health End Points. In addition to our four scenarios, we use two approaches to value health end points across income groups in our CGE modeling framework. For a discussion of alternative approaches, please refer to the Supporting Information.

We first follow the current regulatory approach. We use the value of a statistical life (VSL), which seeks to represent the full economic value of avoiding a small increase in mortality risk, and is defined as the marginal willingness-to-pay to do so. Use of the VSL is supported by theoretical arguments and an increasing number of empirical estimates.[19,22,38] Though studies have examined the potential variation of the VSL with income, we follow regulatory practice and apply the same VSL across income groups,[22] following the U.S. EPA (2012), as shown in Table 1.

Our second valuation approach is an income-based approach. Mortality is represented as 0.5 years of lost income following Matus et al. (2008),[1] differentiated by household income category. This second approach draws from literature on CGE modeling of the health impacts of air pollution, to which our approach contributes. Theoretical and empirical questions remain regarding how to best represent preferences for clean air in economy-wide assessments.[39] To date, such assessments have employed the income-based approach, including nearly all previous analyses using CGE models to assess health impacts of air pollution, including EPA's benefits assessment of the CAA Amendments,[1−3,5,7,30,39,40] although the VSL has also been used, albeit rarely.[20] Unlike the VSL, the use of the income-based approach does not represent the full economic value of risk reductions. However, in contrast to the VSL, it avoids several assumptions: that willingness-to-pay estimates derived from other contexts are transferrable to this policy context and that they are independent of the size of the risk change, existing risk levels, and economic conditions.[41] Additionally, the income-based approach is income-limited, so it precludes that possibility that the value of reduced health risks exceeds expected lifetime consumption.[42]

Morbidity valuations are based on cost of illness estimates (for hospitalizations and ER visits), lost wages (for school lost days), and willingness-to-pay (for minor restricted activity days). The values are shown in Table 1. We do not vary morbidity valuations with household income because we lack relevant empirical relationships between income, cost of illness, and willingness-to-pay. Total valuation of outcomes determines the demand for pollution-related health services in USREP.

■ RESULTS

In the following section, we present results from our four scenarios. We then discuss the effect of valuation.

Ozone-Related Mortality Incidence Rates by Income Group. Figure 1 shows estimated mortality incidence rates associated with changes in ozone concentrations in BASE05 (versus 0 background) and POLICY14 (versus BASE05). Ozone levels in 2005 imply a median mortality incidence rate from ozone-attributable risk of 11 deaths per 100 000 people.

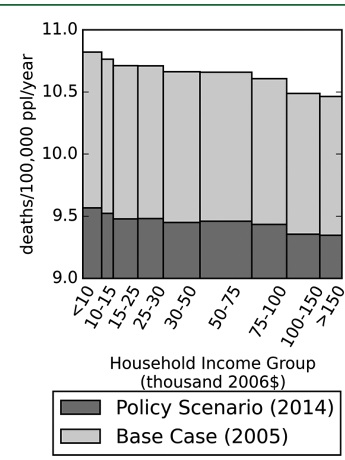

Figure 1. Decreasing pattern with household income of U.S. national incidence rate of acute ozone-related mortalities in the base year (2005) and the policy scenario (2014). Width of each bar represents the proportion of the population within that household income category.

Simulated differences in ambient ozone concentrations across nine income groups in 2005 yield an incidence rate that is 3% higher for the lowest income (<\$10 000) relative to the highest income (>\$150 000) households. At the national scale, mortality incidence rates decrease monotonically with increasing income. Consistent with previous studies, mortality incidence rates can be increasing, flat, or decreasing with increasing income within different regions.[8−12] The population-weighted annual mean of the 8 h daily maximum ozone level is around 40 ppb, averaged nationally. It has a range of about 13 ppb across regions. Nationally, it differs by about 2 ppb across income groups. Regional mortality incidence rates are in the Supporting Information.

Ozone reductions affect the magnitude and distribution of mortality incidence rates with income. Under POLICY14, the modeled magnitude of national ozone-related mortality incidence rates declines by about 1.3 deaths per 100 000 people per year, from 10.8 to 9.5 deaths per 100 000 people per year. The relative pattern of mortality incidence rates still decreases with increasing income but is slightly flatter; POLICY14 decreases the magnitude of the incidence rate by 13% for the lowest income households and by 12% for the highest income households.

Relative Economic Impacts of Reductions with Income Group. Figure 2a shows the relative economic impact of ozone reductions using the VSL to value reduced mortality risk, and Figure 2b uses the income-based approach. Refer to the Supporting Information for annual welfare gains over time and for per capita welfare gains across income groups. In each of the remaining figures, the tick spacing represents the proportion of the population within an income group. In some cases, this has necessitated grouping the labels of the \$10 000−\$15 000 category with the \$15 000−\$25 000 category to accommodate their label spacing in the figure.

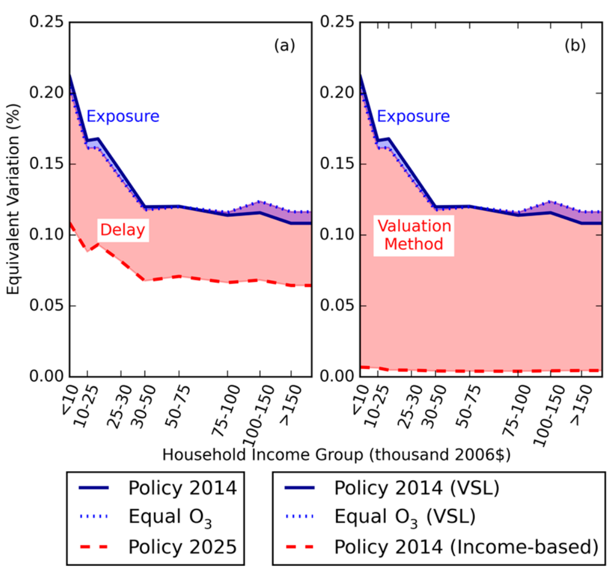

Figure 2. Percent welfare gain by household income group. The solid blue line indicates the use of VSL valuation to represent the full economic value for reduced mortality risk. The blue dotted line shows run with ozone reductions equal across income (EQUALO3). (a) The red dashed line shows implementation delayed to 2025 (POLICY25). The red shading is welfare loss from delay. (b) The red dashed line shows income-based valuation for reduced mortality risk. Red shading is welfare difference between valuations. Tick spacing represents the proportion of the population within that household income category.

The solid line in Figure 2a shows the relative per capita welfare gain (i.e., equivalent variation) from ozone reductions with income (based on the net present value of annual welfare gains versus the BASE05 from 2005 to 2100, discounted at 7%). The median per capita welfare gain decreases with increasing income (95% confidence interval in the Supporting Information). In this relative sense, the lowest income households gain twice as much as the highest incomes (0.21% versus 0.11% of per capita welfare). Similarly, the relative per capita welfare loss from delaying regulations is twice as harmful for low as high-income households.

The per capita welfare gain includes the sum of avoided loss in consumption (e.g., through lost earnings) and lost leisure (e.g., through lost time endowment due to premature mortality). As such, it does not reflect income alone but also reflects the value of government transfers (which can be significant for low-income households) and nonworking time. Per capita welfare gains are noted in the Supporting Information.

The relative per capita welfare gain in Figure 2a denotes the effect of the policy on welfare with respect to welfare under the base case (BASE05). It is a percentage change in per capita welfare under the policy; for example, households with income less than \$10 000 have a gain in per capita welfare of 0.21% under the policy compared to their welfare under the base case.

The gain is relative to a base-case per capita welfare that varies by income group. The variation in welfare with income under the base case is composed of differences in income (which is derived from labor, capital, land, and resources) and variations in rates of taxes and government transfers (for a detailed discussion of within and across group variation in welfare by income category, see Rausch, Metcalf, and Reilly, 2011).[33]

Figure 2a also shows that the welfare loss from delay (in red shading between the solid line and the dashed line) for POLICY25 represents about 50% of the potential gains from POLICY14. The primary effect of the delay is due to discounting of delayed welfare gains. In addition, it should be noted that, over this 11 year period, wages could potentially rise, which could potentially affect the value of both the income-based approach and the VSL approach in ways we have not accounted for by using flat values over this period. However, this effect would be minimal over this period, given small reductions in real median incomes from 2006 to 2014 and an income elasticity of 0.4.[43] For further discussion on the effect of delay with welfare over time, refer to the Supporting Information.

Figures 2a and 3 show the influence of changes in ozone concentrations across income groups on results. The dotted line in Figure 2a presents scenario (4) EQUALO3 that assigns the average change in health outcomes to all households within a region. The blue shaded area in Figure 2a between the solid and dotted lines shows the difference between these analyses in relative per capita welfare. Thus, the blue shaded region depicts the effect of unequal ozone reductions with income, which arise because POLICY14 tends to reduce ozone among low-income households. Figure 3 isolates this effect as a percent change in per capita welfare. The percentage change in Figure 3 represents the difference between the EQUALO3 and POLICY14 across income groups. Figure 3 demonstrates that treating the reductions in ozone levels as equal by income

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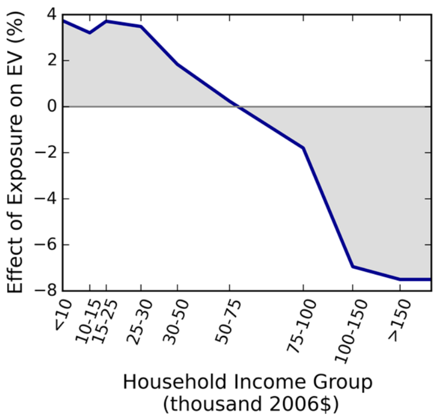

Figure 3. Percent effect of accounting for differential ozone reductions across household income groups on relative welfare gain. Tick spacing represents the proportion of the population within that household income category.

group would understate relative welfare gains for the poor (by about 4%), and overstate them for the rich (by up to 8%). Thus, the effect of unequal ozone reductions explains only on the order of 10% of the fact that POLICY14 yields relative gains that are twice as high for the lowest income households; the rest is explained primarily by the variation in between-category welfare.

Figure 2b uses the income-based approach to value changes in mortality risk, as opposed to using the VSL as in Figure 2a. The per capita welfare gain for households with less than \$10 000 in annual income is 0.007% in Figure 2b instead of 0.22% using the VSL as in Figure 2a. The valuation approach has a larger effect on the relative policy gains than the effect of delay or differences in ozone reductions with income.

Figure 4 shows the normalized relative gains for both valuation approaches. With the income-based approach, households with the lowest incomes still have the highest relative gains; however, instead of monotonically decreasing with income, the relative value of reductions increases for

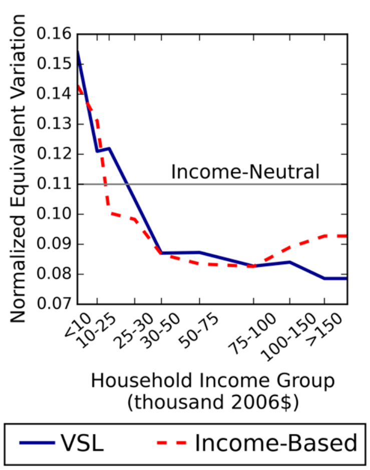

Figure 4. Normalized percent per capita welfare gain of the policy scenario by household income group. The blue solid line employs the VSL-based valuation; the red dashed line indicates the employment of the income-based valuation. Tick spacing represents the proportion of the population within that household income category.

households with incomes higher than \$75 000. Delay has a similar effect using both valuations, foregoing half of the relative gains for the lowest income households, and is about twice as harmful (factor of 1.8) for the lowest compared to the highest income households.

■ DISCUSSION

Previous studies have found different relationships between ambient ozone and income depending on the region of study.[8−12] We find, at the U.S. national scale, in 2005, that modeled ambient ozone levels imply a higher mortality incidence rate for low-income households relative to high-income households. The income variability of the population-weighted annual mean of the 8 h daily maximum ozone level varies by region and differs by about 2 ppb across income groups. A 2 ppb difference is relevant in the U.S. policy context, in which the EPA recently lowered the ambient standard by 5 ppb.[16]

We find, using two valuation approaches, that ozone reduction policies can be relatively more valuable for low-income households. With both approaches, an 11 year delay of ozone reductions is relatively twice as harmful for the lowest income households as the highest income households. The policy scenario favors ozone reductions among low-income households, which further increases the relative benefits for low-income households by about 4%.

This relative analysis places ozone reductions in the context of other sources of economic welfare. Our estimates of the median welfare gain for the lowest-income households are 0.22% (VSL-based) and 0.07% (income-based) and apply to ozone reductions of a median of 4% by region. Previous studies have estimated the total welfare loss from the combined historical effects of ozone and fine particulate matter, e.g., 5% of welfare in 2005 in China or about 2% in Europe in 2005 based on levels from 1970 to 2005.[3,5] Sieg et al. (2004)[24] examined dramatic ozone reductions ranging from 3% to 33% in Southern California, finding a willingness to pay for these reductions ranging from 1% to 3% of annual household income. In magnitude, rather than as a percent of welfare, our benefits per capita do increase with income, consistent with the empirical findings of Tra (2010)[25] (refer to the per capita benefits in the Supporting Information). Comparing several factors that can affect the value of reductions, we find, for this policy scenario, that the difference in the median benefits estimates between the two valuation approaches was larger than the loss from delay and the effect of unequal reductions across income groups.

Our findings have several implications for ozone policy analysis. We identify the potential for policy to produce unequal ozone reductions with income and greater relative economic gains for low-income households. We directly apply two valuation approaches for reduced mortality risks used in EPA analysis of other pollutants under the CAA.[7] Disparities in the results between these approaches highlight the importance of the valuation method, as well as the need for further empirical evidence of the impacts of ozone with income. Our study complements work on risk inequality and fine particulate matter. Fann et al. (2011)[17] describe the potential for targeting fine particulate matter reductions in vulnerable and susceptible subpopulations to improve metrics of risk inequality under policy. Our study explored a wider region at a lower resolution for a different pollutant, ozone. Ozone would be difficult to reduce in a targeted way because it forms regionally, but our

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economic analysis reveals potential benefits for vulnerable populations. In part, this is because our policy scenario reduced ozone-related health risks most among low-income households; however, this effect was small compared to the timing and valuation of the policy. This implies that further action and information about timing and valuation may have a greater effect on estimates of the equity of ozone policy than targeted reductions in ambient ozone.

Although we find that modeled ozone levels can imply different health risks with income, further empirical evidence is needed to understand the relationships of ozone, income, and public health. We focus only on the effect of modeled ozone levels at 36 km resolution at the household's location. Bell and Dominici (2008) noted the relationship between ozone and mortality may be modified by several factors, including underlying health status. Their studies found weak evidence of increased sensitivity to ozone with poverty.[44,45] Uncertainties in concentration−response functions for ozone are large compared to the inequality with income of ozone-related health risks. Reducing uncertainty in the estimates of relationships between ozone and human health would be helpful in estimating the effect of the 2 ppb spread with income found here.

Our results highlight the need for relevant empirical relationships between ozone, income, and economic preferences that represent the full range of income inequality. Various findings suggest that the marginal disutility from health risks, health care access, and health outcomes vary with income, region, and insurance status,[19,46−49] although we lack specific empirical relationships to apply to this case. We were also restricted to nine census household income categories that do not capture the full range of the highest incomes[50] or the considerable variability of consumption within income groups.[33] Considering these factors, our study is not meant to identify an empirical relationship between income and health-related ozone impacts but to develop an approach that can explore the effect of ozone reductions under policy with income.

Several sources of uncertainty will affect ozone-related health impacts. We use constant meteorology to assess the effect of emissions, but weather will affect future ozone levels.[51] Modeled ozone levels are uncertain, which may alter the magnitude of benefits. Although model bias can vary by location,[52] this bias would have to correlate with household income to affect the results by income group. Results are derived at 36 km resolution. Studies have found that resolution can affect estimates of ozone-related health impacts,[53−55] with coarse (36 km) resolution resulting in overestimates, particularly in major urban centers. Thus, we expect our national estimates of ozone-related impacts may be higher than would be calculated at a finer (<36 km) resolution. It is possible that a finer resolution could yield a different pattern of inequality given the spatial variability of both ozone levels and household income. While examining this effect specifically is outside the scope of this study, we test the effect of estimating ozone-related mortality incidence rates across income categories using 36, 12, and 4 km resolutions. We do not find any discernible pattern in the effect of model resolution on inequality in incidence rates, and the effect appears to be minor, especially compared to the other sources of uncertainty (e.g., economic valuation) described here; however, the coarser resolution may also overstate mortality incidences for lower incomes in some regions. Details and results are in the Supporting Information.

In addition to those discussed, there are multiple uncertainties and factors affecting this analysis. USREP is based on simple equations of production and assumptions about behavior that may make household income categories appear homogeneous and diminish the signal with income in these results. Our population projections do not capture the potential interaction of migration and economic mobility. The value of delay will increase with an increasing discount rate. The dynamic element of our approach could be improved by, for example, accounting for climate feedbacks,[56−59] or introducing endogenous implementation of pollution control.[60]

We enhance an integrated modeling framework to represent the health-related economic impacts of ozone pollution and the related benefits of ozone policy. We quantify how inequality in ozone levels, delayed policy action, and approaches to economic valuation affect the relative economic value of ozone policies with household income. We find that ozone reductions in the policy scenario favored reduced mortality risks among low-income households and that reductions were relatively twice as beneficial for the lowest compared to the highest income households. We find that the choice of economic valuation approach had a greater impact on the median benefits than the effect of an 11 year policy delay or differential ozone reductions with income. Empirical and theoretical challenges remain in assessing environmental and health preferences with income in an economy-wide framework. This study demonstrates the potential for differences in relative economic gains across income groups from ozone reductions and supports including analysis across income groups as a complement to current analysis of environmental policy. As empirical relationships between ozone, human health, and income are improved, they can be incorporated into this type of approach to estimate the effect of policy. Our findings suggest that ozone policies may differentially affect health and economic outcomes with income and that ignoring these differences could understate the importance of ozone reductions for low-income households.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b04708.

> Information on ozone modeling, economic modeling, and valuations and alternative valuation methods. Supplemental results on regional mortality incidence rates, effect of resolution, annual welfare gains over time, effect of delay, and confidence intervals for welfare gains. (PDF)

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

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■ REFERENCES

(1) Matus, K.; Yang, T.; Paltsev, S.; Reilly, J.; Nam, K.-M. Toward integrated assessment of environmental change: air pollution health effects in the USA. *Clim. Change* **2008**, *88* (1), 59−92.

(2) Selin, N. E.; Wu, S.-Y.; Nam, K.-M.; Reilly, J. M.; Paltsev, S.; Prinn, R. G.; Webster, M. D. Global health and economic impacts of future ozone pollution. *Environ. Res. Lett.* **2009**, *4* (4), 044014.

(3) Nam, K.-M.; Selin, N. E.; Reilly, J. M.; Paltsev, S. Measuring welfare loss caused by air pollution in Europe: A CGE analysis. *Energy Policy* **2010**, *38* (9), 5059−5071.

(4) Fraas, A. G. The Treatment of Uncertainty in EPA's Analysis of Air Pollution Rules: A Status Report. *J. Benefit-Cost Anal.* **2011**, *2* (2), 1−27.

(5) Matus, K.; Nam, K.-M.; Selin, N. E.; Lamsal, L. N.; Reilly, J. M.; Paltsev, S. Health damages from air pollution in China. *Glob. Environ. Change* **2012**, *22* (1), 55−66.

(6) U.S. Environmental Protection Agency. *Regulatory Impact Analysis for the Final Revisions to the National 1 Ambient Air 2 Quality Standards for Particulate Matter, Office of Air Quality Planning and Standards*; Report EPA-452/R-12−005; U.S. EPA: Research Triangle Park, NC, 2012.

(7) U.S. Environmental Protection Agency. *The Benefits and Costs of the Clean Air Act from 1990 to 2020*; U.S. EPA: Research Triangle Park, NC, 2011.

(8) Grineski, S.; Bolin, B.; Boone, C. Criteria Air Pollution and Marginalized Populations: Environmental Inequity in Metropolitan Phoenix, Arizona*. *Soc. Sci. Q.* **2007**, *88* (2), 535−554.

(9) Liu, F. Who Will Be Protected by EPA's New Ozone and Particulate Matter Standards? *Environ. Sci. Technol.* **1998**, *32* (1), 32A−39A.

(10) Miranda, M. L.; Edwards, S. E.; Keating, M. H.; Paul, C. J. Making the Environmental Justice Grade: The Relative Burden of Air Pollution Exposure in the United States. *Int. J. Environ. Res. Public Health* **2011**, *8* (6), 1755−1771.

(11) Marshall, J. D. Environmental inequality: Air pollution exposures in California's South Coast Air Basin. *Atmos. Environ.* **2008**, *42* (21), 5499−5503.

(12) Liu, F. Urban ozone plumes and population distribution by income and race: a case study of New York and Philadelphia. *J. Air Waste Manage. Assoc.* **1996**, *46* (3), 207−215.

(13) Bento, A.; Freedman, M.; Lang, C. Who Benefits from Environmental Regulation? Evidence from the Clean Air Act Amendments. *Rev. Econ. Stat.* **2015**, *97* (3), 610−622.

(14) Berman, J. D.; Fann, N.; Hollingsworth, J. W.; Pinkerton, K. E.; Rom, W. N.; Szema, A. M.; Breysse, P. N.; White, R. H.; Curriero, F. C. Health Benefits from Large-Scale Ozone Reduction in the United States. *Environ. Health Perspect.* **2012**, *120* (10), 1404−1410.

(15) U.S. Environmental Protection Agency. Cross-State Air Pollution Rule (CSAPR). http://www.epa.gov/airtransport/CSAPR/ (accessed April 28, 2015).

(16) U.S. Environmental Protection Agency. *National Ambient Air Quality Standards for Ozone*; Final rule EPA-HQ-OAR-2008−0699; FRL-9918−43-OAR; Office of Air Quality Planning and Standards: Research Triangle Park, NC, 2015.

(17) Fann, N.; Roman, H. A.; Fulcher, C. M.; Gentile, M. A.; Hubbell, B. J.; Wesson, K.; Levy, J. I. Maximizing Health Benefits and Minimizing Inequality: Incorporating Local-Scale Data in the Design and Evaluation of Air Quality Policies. *Risk Anal.* **2011**, *31* (6), 908−922.

(18) van Kippersluis, H.; Galama, T. J. Wealth and health behavior: Testing the concept of a health cost. *Eur. Econ. Rev.* **2014**, *72*, 197−220.

(19) Viscusi, W. K.; Aldy, J. E. The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World. *J. Risk Uncertain.* **2003**, *27* (1), 5−76.

(20) Chemingui, M. A.; Thabet, C. Taxing CO2 emissions and its ancillary health benefits: a computable general equilibrium analysis for Tunisia. *Middle East Dev. J.* **2014**, *6* (1), 108−145.

(21) Alberini, A.; Ščasný, M. Exploring heterogeneity in the value of a statistical life: Cause of death v. risk perceptions. *Ecol. Econ.* **2013**, *94*, 143−155.

(22) Viscusi, W. K. The devaluation of life. *Regul. Gov* **2009**, *3* (2), 103−127.

(23) Rausch, S.; Metcalf, G. E.; Reilly, J. M.; Paltsev, S. Distributional Impacts of a U.S. Greenhouse Gas Policy: A General Equilibrium Analysis of Carbon Pricing. In *U.S. Energy Tax Policy*; Metcalf, G. E., Ed.; Cambridge University Press: New York, NY, 2010.

(24) Sieg, H.; Smith, V. K.; Banzhaf, H. S.; Walsh, R. Estimating the General Equilibrium Benefits of Large Changes in Spatially Delineated Public Goods*. *Int. Econ. Rev.* **2004**, *45* (4), 1047−1077.

(25) Tra, C. I. A discrete choice equilibrium approach to valuing large environmental changes. *J. Public Econ.* **2010**, *94* (1−2), 183−196.

(26) Tra, C. I. Measuring the General Equilibrium Benefits of Air Quality Regulation in Small Urban Areas. *Land Econ.* **2013**, *89* (2), 291−307.

(27) Vrontisi, Z.; Abrell, J.; Neuwahl, F.; Saveyn, B.; Wagner, F. Economic impacts of EU clean air policies assessed in a CGE framework. *Environ. Sci. Policy* **2016**, *55* (1), 54−64.

(28) Baker, K. R.; Dolwick, P. *Meteorological Modeling Performance Evaluation for the Annual 2005 Continental U.S. 36-km Domain Simulation*; Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency: Research Triangle Park, NC, 2009.

(29) Thompson, T. M.; Rausch, S.; Saari, R. K.; Selin, N. E. A systems approach to evaluating the air quality co-benefits of US carbon policies. *Nat. Clim. Change* **2014**, *4* (10), 917−923.

(30) Saari, R. K.; Selin, N. E.; Rausch, S.; Thompson, T. M. A self-consistent method to assess air quality co-benefits from U.S. climate policies. *J. Air Waste Manage. Assoc.* **2015**, *65* (1), 74−89.

(31) CMAS. *SMOKE v2.7 User's Manual*; The University of North Carolina at Chapel Hill: Chapel Hill, NC, 2010.

DOI: 10.1021/acs.est.6b04708
Environ. Sci. Technol. 2017, 51, 1953−1961

(32) Rausch, S.; Mowers, M. Distributional and efficiency impacts of clean and renewable energy standards for electricity. *Resour. Energy Econ.* **2014**, *36* (2), 556−585.
(33) Rausch, S.; Metcalf, G. E.; Reilly, J. M. Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households. *Energy Econ* **2011**, *33* (1), S20−S33.
(34) Lanz, B.; Rausch, S. General equilibrium, electricity generation technologies and the cost of carbon abatement: A structural sensitivity analysis. *Energy Econ.* **2011**, *33* (5), 1035−1047.
(35) Rausch, S.; Karplus, V. J. *Markets versus Regulation: The Efficiency and Distributional Impacts of U.S. Climate Policy Proposals*; Technical Report; MIT Joint Program on the Science and Policy of Global Change: Cambridge, MA, 2014.
(36) Caron, J.; Rausch, S.; Winchester, N. Leakage from sub-national climate policy: The case of California's cap-and-trade program. *Energy J.* **2015**, *36* (2), 167−190.
(37) Paltsev, S.; Capros, P. Cost Concepts for Climate Change Mitigation. *Clim. Change Econ.* **2013**, *04* (1), 1340003.
(38) Cropper, M.; Hammitt, J. K.; Robinson, L. A. Valuing Mortality Risk Reductions: Progress and Challenges. *Annu. Rev. Resour. Econ.* **2011**, *3* (1), 313−336.
(39) Carbone, J. C.; Smith, V. K. Valuing Nature in General Equilibrium. *J. Environ. Econ. Manag.* **2013**, *66* (1), 72−89.
(40) Xie, Y.; Dai, H.; Dong, H.; Hanaoka, T.; Masui, T. Economic Impacts from PM2.5 Pollution-Related Health Effects in China: A Provincial-Level Analysis. *Environ. Sci. Technol.* **2016**, *50* (9), 4836−4843.
(41) Smith, V. K.; Carbone, J. C. Should Benefit−Cost Analyses Take Account of General Equilibrium Effects? *Res. Law Econ.* **2007**, *23*, 247−272.
(42) Solow, R. A few comments on "Sustainability and the measurement of wealth. *Environ. Dev. Econ.* **2012**, *17* (03), 354−355.
(43) Hammitt, J. K.; Robinson, L. A. The Income Elasticity of the Value per Statistical Life: Transferring Estimates between High and Low Income Populations. *J. Benefit-Cost Anal* **2011**, *2* (1), 1−29.
(44) Bell, M. L.; Dominici, F. Effect Modification by Community Characteristics on the Short-term Effects of Ozone Exposure and Mortality in 98 US Communities. *Am. J. Epidemiol.* **2008**, *167* (8), 986−997.
(45) Bell, M. L.; Zanobetti, A.; Dominici, F. Who is More Affected by Ozone Pollution? A Systematic Review and Meta-Analysis. *Am. J. Epidemiol.* **2014**, *180* (1), 15−28.
(46) Van Ourti, T.; van Doorslaer, E.; Koolman, X. The effect of income growth and inequality on health inequality: Theory and empirical evidence from the European Panel. *J. Health Econ.* **2009**, *28* (3), 525−539.
(47) Jones, A. M.; Rice, N.; Robone, S.; Dias, P. R. Inequality and polarisation in health systems' responsiveness: A cross-country analysis. *J. Health Econ.* **2011**, *30* (4), 616−625.
(48) Wilper, A. P.; Woolhandler, S.; Lasser, K. E.; McCormick, D.; Bor, D. H.; Himmelstein, D. U. Health Insurance and Mortality in US Adults. *Am. J. Public Health* **2009**, *99* (12), 2289−2295.
(49) Schoen, C.; Radley, D. C.; Riley, P.; Lippa, J. A.; Berenson, J.; Dermody, C.; Shih, A. Health Care in the Two Americas: Findings from the Scorecard on State Health System Performance for Low-Income Populations. http://www.commonwealthfund.org/publications/fund-reports/2013/sep/low-income-scorecard (accessed April 20, 2015).
(50) Piketty, T.; Saez, E. Top Incomes and the Great Recession: Recent Evolutions and Policy Implications. *IMF Econ. Rev.* **2013**, *61* (3), 456−478.
(51) Jhun, I.; Coull, B. A.; Schwartz, J.; Hubbell, B.; Koutrakis, P. The impact of weather changes on air quality and health in the United States in 1994−2012. *Environ. Res. Lett.* **2015**, *10* (8), 084009.
(52) Bravo, M. A.; Fuentes, M.; Zhang, Y.; Burr, M. J.; Bell, M. L. Comparison of exposure estimation methods for air pollutants: Ambient monitoring data and regional air quality simulation. *Environ. Res.* **2012**, *116*, 1−10.
(53) Thompson, T. M.; Selin, N. E. Influence of air quality model resolution on uncertainty associated with health impacts. *Atmos. Chem. Phys.* **2012**, *12* (20), 9753−9762.
(54) Thompson, T. M.; Saari, R. K.; Selin, N. E. Air quality resolution for health impact assessment: influence of regional characteristics. *Atmos. Chem. Phys.* **2014**, *14* (2), 969−978.
(55) Punger, E. M.; West, J. J. The effect of grid resolution on estimates of the burden of ozone and fine particulate matter on premature mortality in the United States. *Air Qual., Atmos. Health* **2013**, *6* (3), 563−573.
(56) Knowlton, K.; Rosenthal, J. E.; Hogrefe, C.; Lynn, B.; Gaffin, S.; Goldberg, R.; Rosenzweig, C.; Civerolo, K.; Ku, J.-Y.; Kinney, P. L. Assessing Ozone-Related Health Impacts under a Changing Climate. *Environ. Health Perspect.* **2004**, *112* (15), 1557−1563.
(57) Bell, M. L.; Goldberg, R.; Hogrefe, C.; Kinney, P. L.; Knowlton, K.; Lynn, B.; Rosenthal, J.; Rosenzweig, C.; Patz, J. A. Climate change, ambient ozone, and health in 50 US cities. *Clim. Change* **2007**, *82* (1−2), 61−76.
(58) West, J. J.; Szopa, S.; Hauglustaine, D. A. Human mortality effects of future concentrations of tropospheric ozone. *C. R. Geosci.* **2007**, *339* (11−12), 775−783.
(59) Chang, H. H.; Zhou, J.; Fuentes, M. Impact of Climate Change on Ambient Ozone Level and Mortality in Southeastern United States. *Int. J. Environ. Res. Public Health* **2010**, *7* (7), 2866−2880.
(60) Nam, K.-M.; Waugh, C. J.; Paltsev, S.; Reilly, J. M.; Karplus, V. J. Carbon co-benefits of tighter SO2 and NOx regulations in China. *Glob. Environ. Change* **2013**, *23* (6), 1648−1661.
(61) Ito, K.; De Leon, S. F.; Lippmann, M. Associations Between Ozone and Daily Mortality: Analysis and Meta-Analysis. *Epidemiology* **2005**, *16* (4), 446−457.
(62) Schwartz, J. How sensitive is the association between ozone and daily deaths to control for temperature? *Am. J. Respir. Crit. Care Med.* **2005**, *171* (6), 627−631.
(63) Bell, M. L.; McDermott, A.; Zeger, S. L.; Samet, J. M.; Dominici, F. Ozone and short-term mortality in 95 US urban communities, 1987−2000. *JAMA* **2004**, *292* (19), 2372−2378.
(64) Bell, M. L.; Dominici, F.; Samet, J. M. A meta-analysis of time-series studies of ozone and mortality with comparison to the national morbidity, mortality, and air pollution study. *Epidemiol. Camb. Mass* **2005**, *16* (4), 436−445.
(65) Levy, J. I.; Chemerynski, S. M.; Sarnat, J. A. Ozone exposure and mortality: an empiric bayes metaregression analysis. *Epidemiol. Camb. Mass* **2005**, *16* (4), 458−468.
(66) Huang, Y.; Dominici, F.; Bell, M. L. Bayesian hierarchical distributed lag models for summer ozone exposure and cardio-respiratory mortality. *Environmetrics* **2005**, *16* (5), 547−562.
(67) Schwartz, J. Short term fluctuations in air pollution and hospital admissions of the elderly for respiratory disease. *Thorax* **1995**, *50* (5), 531−538.
(68) Schwartz, J. PM10 Ozone, and Hospital Admissions for the Elderly in Minneapolis-St. Paul, Minnesota. *Arch. Environ. Health* **1994**, *49* (5), 366−374.
(69) Schwartz, J. Air pollution and hospital admissions for the elderly in Detroit, Michigan. *Am. J. Respir. Crit. Care Med.* **1994**, *150* (3), 648−655.
(70) Moolgavkar, S. H.; Luebeck, E. G.; Anderson, E. L. Air Pollution and Hospital Admissions for Respiratory Causes in Minneapolis-St. Paul and Birmingham. *Epidemiology* **1997**, *8* (4), 364−370.
(71) Burnett, R. T.; Smith-Doiron, M.; Stieb, D.; Raizenne, M. E.; Brook, J. R.; Dales, R. E.; Leech, J. A.; Cakmak, S.; Krewski, D. Association between Ozone and Hospitalization for Acute Respiratory Diseases in Children Less than 2 Years of Age. *Am. J. Epidemiol.* **2001**, *153* (5), 444−452.
(72) Jaffe, D. H.; Singer, M. E.; Rimm, A. A. Air pollution and emergency department visits for asthma among Ohio Medicaid recipients, 1991−1996. *Environ. Res.* **2003**, *91* (1), 21−28.
(73) Peel, J. L.; Tolbert, P. E.; Klein, M.; Metzger, K. B.; Flanders, W. D.; Todd, K.; Mulholland, J. A.; Ryan, P. B.; Frumkin, H. Ambient Air

DOI: 10.1021/acs.est.6b04708
Environ. Sci. Technol. 2017, 51, 1953−1961

Pollution and Respiratory Emergency Department Visits. *Epidemiology* **2005**, *16* (2), 164−174.
(74) Wilson, A. M.; Wake, C. P.; Kelly, T.; Salloway, J. C. Air pollution, weather, and respiratory emergency room visits in two northern New England cities: an ecological time-series study. *Environ. Res.* **2005**, *97* (3), 312−321.
(75) Ostro, B. D.; Rothschild, S. Air pollution and acute respiratory morbidity: An observational study of multiple pollutants. *Environ. Res.* **1989**, *50* (2), 238−247.
(76) Gilliland, F. D.; Berhane, K.; Rappaport, E. B.; Thomas, D. C.; Avol, E.; Gauderman, W. J.; London, S. J.; Margolis, H. G.; McConnell, R.; Islam, K. T.; Peters, J. M. The effects of ambient air pollution on school absenteeism due to respiratory illnesses. *Epidemiol. Camb. Mass* **2001**, *12* (1), 43−54.
(77) Chen, L.; Jennison, B. L.; Yang, W.; Omaye, S. T. Elementary school absenteeism and air pollution. *Inhalation Toxicol.* **2000**, *12* (11), 997−1016.

DOI: 10.1021/acs.est.6b04708
Environ. Sci. Technol. 2017, 51, 1953−1961

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