

**Efficient Pollution Regulations: Getting the Prices Right**

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## Abstract

This paper argues there is a tremendous potential welfare gain from explicitly including marginal damages into pollution regulation. Regulations based on firm specific marginal damages will set efficient aggregate emission caps and differentiate permits efficiently to get the emission prices right for every source. The paper develops estimates of the marginal damages, and efficient trading ratios, for the nearly 10,000 distinct sources of air pollution in the coterminous U.S. Prices are hundreds of times higher for metropolitan compared to rural emissions. An example using a collection of 660 coal-fired power plants is used to estimate the welfare benefits of efficient regulations. The additional benefits are an order of magnitude larger than the reported gains from moving from standards to cost effectiveness (tradeable permits). These newly available marginal damages will lead to a new generation of efficient pollution regulations.

Keywords: environmental regulation, air pollution, allowance trading, valuing damages

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# I. Introduction

Early efforts to control air pollution employed standards. Such command and control policies are excessively costly because they do not take inter-firm differences in marginal damages and marginal abatement costs into account. To reduce these costs, economists have long advocated market-based approaches to regulate pollution such as emission taxes or tradable permits (Montgomery, 1972; Baumol, Oates, 1988). Although taxes are popular in the economics literature, they have rarely been implemented to control pollution. Instead, regulatory agencies throughout the world have favored tradable permits when implementing market-based policies (Dales 1968; Montgomery 1972; Tietenberg 1980). Specifically, governments have used undifferentiated permits that allow firms to trade allowances on a ton-for-ton basis. The goal of such policies is cost effectiveness: minimizing the abatement cost of reaching a prespecified aggregate pollution target. Such trading regimes do not recognize that emissions may cause different amounts of damage depending upon where they occur. These policies often rely upon arbitrary aggregate targets. This paper advocates that regulations move from cost effectiveness to efficiency by relying on detailed information about source-specific marginal damages. The paper develops a theoretical treatment for an efficient trading program and it also estimates the marginal damages of emissions for nearly 10,000 distinct air pollution sources in the contiguous United States. To provide a convincing case of the welfare advantages of moving from cost effectiveness to efficiency, a case study using 660 power plants is presented.

The theoretical treatment in this paper builds on earlier efforts to include marginal damages into a trading regime (Montgomery, 1972; Baumol, Oates, 1988; Farrow et al., 2005; Shadbegian et al., 2006). One strategy in the literature suggested subdividing regulated regions into small markets each governed by a distinct permit system (Tietenberg, 1980). Unfortunately, this approach may create thin markets with few sources trading in any single market. Because pollution is often transported long distances, emissions in one zone would also affect other nearby zones making this approach difficult to implement. Ambient permit systems would establish markets for each receptor point (Montgomery, 1972; Baumol and Oates, 1988). Firms must buy ambient permits in each market that is affected by their emissions. Unfortunately, this solution is not practical because firms would have to participate in myriad markets and they would need to understand the complex relationship between their own emissions, the emissions of other firms, meteorology, and atmospheric chemistry. A variant of ambient permits is a system of pollution offsets (Atkinson and Tietenberg, 1982; Krupnick et al., 1983). This program requires firms to buy offsets from other existing sources if additional emissions violate ambient standards. The pollution offset approach suffers from the same general problem of complexity found in the ambient permit systems. An important alternative to ambient systems and offsets is to rely on fixed exchange rates between regulated sources (Klaassen, 1994).

In an early example of this approach, firms trade allowances based on the weighted sum of the impact of their emissions at all receptors where an ambient standard is binding (Klaassen, 1994). Alternatively, fixed exchange rates could be based on the relative impact of emissions across all receptors (Farrow et al., 2005).

In section II, we develop a theoretical model that builds especially on the earlier literature focusing on fixed exchange rates. The theoretical model clarifies two important advantages of incorporating marginal damages into regulatory policy. First, the regulator can determine the optimal aggregate emission cap by equating expected marginal cost to expected marginal damage. With information on marginal damages, aggregate quotas no longer need to be set arbitrarily. Second, regulators can establish fixed exchange rates proportional to the ratio of each firm’s marginal damages to allocate abatement efficiently amongst firms. Facing these exchange rates dictated by the regulator, firms effectively trade in damages and not tons. We show that this structure induces firms to equate their individual marginal costs to their individual marginal damages, resulting in efficient pollution control.

Section III describes the methodology used in the paper to calculate the marginal damages across 10,000 distinct air pollution sources in the contiguous U.S. Marginal damages are calculated using a traditional integrated assessment model, the Air Pollution Emission Experiments and Policy analysis model, APEEP, (Muller and Mendelsohn, 2007). This model tracks the consequences of emissions through air quality modeling, exposure, dose response, and valuation. What is most unique about this calculation of marginal damages is how APEEP is used. The model begins by computing total damages from the baseline level of emissions of particulate matter ( $PM_{2.5}$  and  $PM_{10-PM_{2.5}}$ ), nitrogen oxides ( $NO_x$ ), sulfur dioxide ( $SO_2$ ), volatile organic compounds (VOC), and ammonia ( $NH_3$ ) from existing sources across the U.S. Next, one ton of a specific pollutant is added to the baseline emissions from a particular source. Total damages are recomputed. The resulting change in total damages is the marginal damage of the specific pollutant at the particular source where the ton was added. Note that this methodology captures the damages from secondary pollution formation through atmospheric chemistry and properly attributes the change in damages back to the source of emission. This experiment is repeated for the nearly 10,000 distinct sources in the contiguous U.S and for the six pollutants listed above.

Section IV reports the marginal damage results. We first explore the statistical distribution of the marginal damages for each of the six pollutants across all counties in the U.S. We then compute efficient trading ratios for sources in specific quantiles of the  $NO_x$ ,  $SO_2$ , and  $PM_{2.5}$  distributions. We find the largest ratios are between rural sources and sources in the largest cities. Another important source of variation in marginal damages is stack height. By matching ground level sources to a nearby power plant and computing the efficient trading ratio, we show that ground level emissions are more harmful than emissions from tall stacks, especially in cities.

Section V illustrates the welfare gain of an efficient policy relative to cost effective regulations using a case study of 660 electric generating units. These units comprise 80% of the emissions that were regulated under the system of tradable permits governing SO<sub>2</sub> emissions established by Title IV of the Clean Air Act Amendments of 1990 (CAAA). The cost savings from introducing undifferentiated tradeable permits (cost effectiveness), relative to command-and-control policy, for these plants was estimated to be \$150 million, annually (Keohane 2006). We compute the additional welfare gains from an efficient differentiated permit system, relative to the current system of tradable permits, that relies on the marginal damages of SO<sub>2</sub> emissions from these plants. The first simulation shows the welfare gains from using marginal damages to set the optimal aggregate emission cap. The second simulation shows the additional welfare gains of equating marginal cost to marginal damage for each of the 660 power plants. The total estimated welfare gain of moving to efficient regulations is between \$1.8 billion and \$3.3 billion, annually, which is about 10 times larger than the cost savings due to shifting from command and control regulations to the undifferentiated permit system in Title IV.

## II. Theoretical Model

Historically, regulators have lacked information on firm-specific abatement costs and the damages due to each firm's emissions. As a result, the earliest pollution policy consisted of command and control tools to limit pollution. Such policies produced large deadweight losses because they did not take inter-firm differences in marginal damages and marginal costs into account. However, partially due to the strong urging of economists, regulators have moved towards market-based approaches (Tietenberg, 1980; Baumol, Oates 1988). In the U.S., federal air pollution regulators implemented two undifferentiated permits systems in the 1990's: a program to reduce SO<sub>2</sub> emissions from electric generators and a program to control ozone by reducing NO<sub>x</sub> emissions in the eastern US. The ton-for-ton trading allowed by these policies has helped to lower aggregate abatement costs by encouraging firms with high marginal abatement costs to do relatively less abatement and firms with lower costs to conduct comparatively more abatement. These new programs are cost effective, they minimize the abatement cost of reaching prespecified aggregate emission targets. However, these trading programs are not efficient. The aggregate targets are set arbitrarily and the ton-for-ton trading embodied in these programs does not equate firm-specific marginal costs to marginal damages.

We begin the theoretical modeling by looking at a cost effective undifferentiated permit system. The regulator<sup>1</sup> sets an arbitrary aggregate cap on emissions ( $\bar{E}$ ). The regulator then allocates the permits (which total to  $\bar{E}$ ) across the regulated firms. The regulator's objective is to minimize the sum of abatement costs,

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<sup>1</sup>In the case of the CAAA, the aggregate emission cap was set by Congress.

subject to the constraint that the sum of the (N) regulated firms' emissions ( $\sum_{i=1}^N E_i$ ) is less than or equal to the aggregate cap ( $\bar{E}$ ).

$$\begin{aligned} \min_{E_i} \quad & \sum_{i=1}^N C_i(E_i) \\ \text{s.t.} \quad & \bar{E} \geq \sum_{i=1}^N E_i \end{aligned} \tag{1}$$

Note that the cost function is expressed in terms of emissions (not abatement). Consequently, we assume that  $\frac{\partial C_i}{\partial E_i} < 0$  and that  $\frac{\partial^2 C_i}{\partial E_i^2} < 0$ . We assume that the regulator does not know the marginal cost function of each firm,  $C_i(E_i)$ , but the regulator does know the expected marginal cost function across all firms. The Lagrangian associated with the regulator's cost-minimization problem is the following, where ( $\rho$ ) is a Lagrange multiplier:

$$L = \sum_{i=1}^N C_i(E_i) + \rho(\bar{E} - \sum_{i=1}^N E_i). \tag{2}$$

The first-order condition of equation (2) shows that cost-minimization occurs when marginal abatement costs ( $-\frac{\partial C_i}{\partial E_i}$ ) are equated to the marginal value of changing the abatement constraint ( $\rho$ ).

$$\rho = -\left(\frac{\partial C_i}{\partial E_i}\right) \tag{3}$$

Since ( $\rho$ ) is constant, marginal costs are equated across firms. This solution is cost-effective (Montgomery, 1972). When firms are faced with an undifferentiated permit program, their objective is to minimize the sum of their abatement costs and the cost of buying permits given the initial allocation of permits ( $E_i^0$ ) and the price of permits on the market ( $P$ ):

$$\min_{E_i} C_i(E_i) + P(E_i - E_i^0). \tag{4}$$

The first order condition of equation (4) is:

$$P = - \left( \frac{\partial C_i}{\partial E_i} \right). \quad (5)$$

The firm engages in abatement up to the level that equates their marginal abatement cost to the market price of permits ( $P$ ). Since every firm faces the same permit price, marginal costs are equated across firms. In a competitive cap-and-trade market,  $P = \rho$ : the permit price ( $P$ ) reflects the shadow price affixed to the aggregate cap ( $\rho$ ). Hence, the trading outcome in (5) is the cost-effective solution that is shown in (3).

We now explore how a permit trading system can achieve allocative efficiency if the regulator knows the marginal damages of emissions from each firm. We assume the regulator knows firm-specific marginal damages with certainty<sup>2</sup>. The damages due to emissions from firm (i),  $D_i(E_i)$ , consist of the change (decrease) in utility among all of the consumers exposed to the emissions from firm (i). Air pollution from any one source (i) affects the air quality experienced by many people. The damage function for any one firm's emissions is the sum of the damages experienced by each consumer (Samuelson, 1954). In an efficient program, the objective of the regulator is to minimize the sum of abatement costs and damages across all firms subject to the constraint that the sum of all regulated firms' emissions is less than or equal to the aggregate cap ( $E^*$ ).

$$\begin{aligned} \min \sum_{i=1}^N D_i(E_i) + \sum_{i=1}^N C_i(E_i) \\ \text{s.t. } E^* \geq \sum_{i=1}^N E_i \end{aligned} \quad (6)$$

We assume  $\frac{\partial D_i}{\partial E_i} > 0$  and  $\frac{\partial^2 D_i}{\partial E_i^2} \leq 0$ . The Lagrangian expression corresponding to (6) is shown in (7) where ( $\lambda$ ) is a Lagrange multiplier:

$$L = \sum_{i=1}^N D_i(E_i) + \sum_{i=1}^N C_i(E_i) + \lambda(E^* - \sum_{i=1}^N E_i). \quad (7)$$

Differentiating (7) with respect to  $E_i$  and rearranging yields:

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<sup>2</sup>In the empirical section we provide source-specific estimates of the marginal damages caused by emissions of six air pollutants in the U.S. Because the regulator knows source-specific marginal damages, they also can derive the expected marginal damage across regulated sources.

$$\lambda = \left( \frac{\partial D_i}{\partial E_i} \right) + \left( \frac{\partial C_i}{\partial E_i} \right). \quad (8)$$

In order to implement an efficient permit trading program the regulator must first determine the optimal aggregate emission cap ( $E^*$ ). The regulator is seeking a level of emissions that leads to  $\lambda = 0$ , equating marginal damages to marginal costs for every firm (Baumol, Oates, 1988):

$$\left( \frac{\partial D_i}{\partial E_i} \right) = - \left( \frac{\partial C_i}{\partial E_i} \right) \quad (9)$$

and

$$\left( \frac{\partial D_j}{\partial E_j} \right) = - \left( \frac{\partial C_j}{\partial E_j} \right) : \nabla_j. \quad (10)$$

It follows from the first-order condition that the ratio of marginal damages between two firms should be equated with the ratio of marginal costs.

$$\frac{\frac{\partial D_i}{\partial E_i}}{\frac{\partial D_j}{\partial E_j}} = \frac{\frac{\partial C_i}{\partial E_i}}{\frac{\partial C_j}{\partial E_j}} \quad (11)$$

The aggregate damages (TD) due to the emissions of all (N) sources is the sum of the source-specific marginal damage times the emissions discharged by each source. Under an efficient policy, because marginal damages are equal to marginal costs, the aggregate value of emissions (TD) is the same whether a unit of emission is multiplied times the marginal cost of abatement or by the marginal damage of emissions.

$$TD = \sum_{i=1}^N E_i \left( \frac{\partial D_i}{\partial E_i} \right) = - \sum_{i=1}^N E_i \left( \frac{\partial C_i}{\partial E_i} \right) \quad (12)$$

Multiplying equation (12) times  $(E^*/E^*)$ , maintains the equality.

$$TD^* = E^* \sum_{i=1}^N \frac{E_i}{E^*} \left( \frac{\partial D_i}{\partial E_i} \right) = E^* \sum_{i=1}^N \frac{E_i}{E^*} \left( \frac{\partial C_i}{\partial E_i} \right) \quad (13)$$



The  $(E_i/E^*)$  term is the share of total emissions produced by firm (i): the weight attributed to firm (i)'s marginal damage. Hence, the quantity  $\sum_{i=1}^N \frac{E_i}{E^*} \left( \frac{\partial D_i}{\partial E_i} \right)$  is the emission-weighted expected marginal damage function and the  $E^* \sum_{i=1}^N \frac{E_i}{E^*} \left( \frac{\partial C_i}{\partial E_i} \right)$  term is the emission-weighted expected marginal cost function. This approach gives relatively more weight to sources that emit greater tonnage than sources that discharge a small quantity of pollution. The regulator's task is to choose the aggregate emission cap ( $E^*$ ) so that expected marginal damages are equal to expected marginal costs. The optimal aggregate emission cap ( $E^*$ ) determines an optimal level of total damages,  $TD^*$ , which is equal to  $E^*$  multiplied by the expected marginal damage or  $E^*$  multiplied by the expected marginal cost. If an arbitrary aggregate cap ( $\bar{E}$ ) is selected and it is too high, ( $\bar{E} > E^*$ ), marginal costs will be less than marginal damages, and the shadow price will be positive ( $\lambda > 0$ ). If the cap is too low, ( $\bar{E} < E^*$ ), marginal costs will exceed marginal damages, and the shadow price will be negative ( $\lambda < 0$ ).

With the optimal level of total damages determined, the regulator must identify an initial allocation of permits. However, with differentiated permits the regulator must focus on allocating total damages across regulated sources. The total damage implied by the initial allocation of permits must add up exactly to the optimal aggregate damage,  $TD^*$ . Of course, there may be many combinations of initial permits across the (N) firms that will satisfy this condition.

In addition to setting the aggregate emission cap ( $E^*$ ) in an efficient trading regime, the regulator must ensure that the efficient allocation of abatement will result from trading. One strategy to achieve the efficient allocation is to set fixed trading ratios between firms that are equal to the inverse ratio of firms' marginal damages.

$$\frac{\frac{\partial D_i}{\partial E_i}}{\frac{\partial D_j}{\partial E_j}} = \frac{\Delta E_j}{\Delta E_i} \quad (14)$$

By setting these exchange rates, the regulator is effectively encouraging firms to trade in marginal damage-weighted tons. The fixed exchange rates get the relative prices of pollution right across sources. A critical property of these exchange rates is evident when we rearrange terms: trades between any firms (i) and (j) will not change aggregate damages.

$$\Delta E_j \left( \frac{\partial D_j}{\partial E_j} \right) - \Delta E_i \left( \frac{\partial D_i}{\partial E_i} \right) = 0 \quad (15)$$

Provided that the initial allocation generates total damages equal to ( $TD^*$ ), the trading ratios keep the aggregate damages constant at the optimal level before and after trades.

We now explore whether a system of differentiated permits with these fixed exchange rates and an initial allocation of ( $E^*$ ) permits that generates the optimal aggregate damages is efficient. We assume that a profit-maximizing firm ( $i$ ) is given an initial endowment of permits,  $E_i^0$ , and that the relative trading ratios between firm ( $i$ ) and each firm ( $j$ ), is  $\frac{\Delta E_j}{\Delta E_i}$ . The permit price for each firm ( $j$ ), is  $P_j$ . Firm ( $i$ ) seeks to minimize its abatement costs and the costs of buying permits from the other regulated firms.

$$\min_{E_i} C(E_i) + \sum_{j=1}^J P_j \left( \frac{\Delta E_j}{\Delta E_i} \right) (E_i - E_i^0). \quad (16)$$

The first-order condition for cost-minimization is:

$$-\left( \frac{\partial C_i}{\partial E_i} \right) = P_j \left( \frac{\Delta E_j}{\Delta E_i} \right) = P_i. \quad (17)$$

Firm ( $i$ ) will equate its marginal cost to the weighted price of a permit from another source ( $j$ ). (If source ( $j$ ) has marginal damages equivalent to source ( $i$ ), then the prices attributed to their permits are equal.) With many firms, trading across sources will equate the price,  $P_i$ , to the weighted price of permits for all sources ( $j$ ):  $P_j \left( \frac{\Delta E_j}{\Delta E_i} \right) = P_i$ . Specifically, if the price of permits for any source ( $i$ ) were less than the weighted price of any  $P_j$ , other firms would buy allowances from ( $i$ ) because these permits are cheaper than other available permits. Firms recognizing this bargain would drive up the price,  $P_i$ , until (17) is satisfied. Similarly, if any source ( $i$ ) had a price that was higher than the weighted price of  $P_j$ , firms buying permits would turn to other sources because an allowance from firm ( $i$ ) is more expensive than other available permits. Firms holding allowances for ( $i$ ) would be induced to sell because of the premium on ( $i$ ) relative to the value of other permits. Because the market equates  $P_i$  to the weighted price of permits for all sources ( $j$ ), trading will make the ratio of prices equal to the inverse of the fixed exchange rates:  $(\Delta E_j / \Delta E_i) = (P_i / P_j)$ . Because the inverse of the fixed exchange rates are equal to the ratio of marginal damages, the ratio of prices will be equal to the ratio of marginal damages and marginal costs:  $P_i / P_j = \left( \frac{\partial D_i}{\partial E_i} \right) / \left( \frac{\partial D_j}{\partial E_j} \right) = \left( \frac{\partial C_i}{\partial E_i} \right) / \left( \frac{\partial C_{jj}}{\partial E_j} \right)$ .

This implies that in the first-order condition in (17), firm ( $i$ ) equates its marginal cost to its marginal damage: the efficient outcome. Further, because the aggregate marginal damage,  $TD^*$ , was set optimally in the initial allocation of permits and because trading does not change the level of damages, the aggregate level of damages remains at  $TD^*$ .

The welfare gain to society of an efficient regulatory program versus a cost effective program is the total cost difference between the two policies. This consists of two components. First, there is the welfare

advantage of determining the optimal level of aggregate permits ( $E^*$ ), or aggregate damages ( $TD^*$ ), relative to an arbitrary cap. Second, there is the additional welfare gain of allocating those permits across firms so that marginal damages equal marginal cost at every firm. The total welfare gain from these two components is shown in (18), where ( $\tilde{E}_i$ ) reflects emissions from firm (i) under the cost effective program and ( $E_i^*$ ) is the efficient level of emissions produced by firm (i).

$$W = \sum_{i=1}^N [C_i(E_i^*) + D_i(E_i^*)] - \sum_{i=1}^N [C_i(\tilde{E}_i) + D_i(\tilde{E}_i)] \quad (18)$$

### III. Empirical Model for Computing Marginal Damages

The Air Pollution Emission Experiments and Policy analysis model, APEEP, (Muller and Mendelsohn, 2007) is used to calculate the marginal damage of emissions for nearly 10,000 distinct sources of air pollution in the U.S. Emissions of six pollutants are tracked: sulfur dioxide ( $SO_2$ ), volatile organic compounds ( $VOC$ ), nitrogen oxides ( $NO_x$ ), fine particulates ( $PM_{2.5}$ ), coarse particulates ( $PM_{10} - PM_{2.5}$ ) and ammonia ( $NH_3$ ). This is accomplished using the following algorithm. The model begins by estimating total damages due to baseline emissions (the model is calibrated to 2002) at each of the sources in the model (USEPA, 2006). Next, APEEP adds one ton of one pollutant to one source and recomputes national dollar damages. The marginal damage is the difference between the damages due to baseline emissions and the damages after adding the additional ton. Note that this method captures secondary pollutants, such as certain components of fine particulate matter and ozone, that are formed from original emissions and ascribes the damage due to such secondary pollutants back to the source of emissions. The marginal damage is shown in the following expression.

$$MD_{ps} = \sum_{r=1}^R (\delta_{re}) - \sum_{r=1}^R (\delta_{rb}) \quad (19)$$

where:  $MD_{ps}$  = damage per ton of pollutant (p), emitted from source (s).

$\delta$  = dollar damage

$r$  = receptor county

$e$  = emissions perturbation: +1 ton of (p) added to the baseline emissions at source (s).

$b$  = 2002 baseline emissions

After computing the marginal damage for a pollutant (p) and source (s), this experiment is repeated for each of the six pollutants covered in this paper and approximately 10,000 distinct sources in the U.S. The distinct sources are defined by the U.S. Environmental Protection Agency (USEPA) with many small sources grouped together as a single county area source. The complete set of marginal damages required 60,000 repetitions of the experiment outlined above. These marginal damages are available from the authors (website citation forthcoming).

A detailed technical description of the APEEP model is available (Muller and Mendelsohn, 2007). In this paper, we briefly highlight the basic structure of the model and some of the most important assumptions in the model. The model employs emission data for each criteria air pollutant (and ammonia) provided by the USEPA's 2002 National Emission Inventory (USEPA, 2006). Concentrations due to the baseline levels of emissions are predicted by the air quality models in APEEP. The accuracy of the predicted pollution levels produced by these models has been statistically tested and documented (Muller and Mendelsohn, 2007). Exposures are computed by multiplying county-level populations times county-level pollution concentrations. In APEEP, populations include number of people, crops produced, timber harvested, an inventory of man-made materials, visibility resources, and recreation usage (for each county in the contiguous U.S.). In the next stage, we use peer-reviewed concentration-response functions to translate exposures into the number of physical effects: these include premature mortalities, cases of illness, and crops lost, among others. APEEP uses findings from Pope et al. (2002) to model the relationship between chronic exposures to  $PM_{2.5}$  and adult mortality rates. For the effect of  $PM_{2.5}$  on infant mortality rates, we employ the recent Woodruff et al. (2006) study. APEEP also captures the relationship between exposures to tropospheric ozone and adult mortality rates using the study by Bell et al., (2004). Finally, to value premature mortality risks, we employ two approaches. Our conservative estimate relies on a meta-analysis (Mrozek and Taylor, 2002) that employs findings from nearly 40 revealed preference studies, concluding that an additional  $\left(\frac{1}{10,000}\right)$  chance of death is worth \$200 per year. We then compute the value of a life year, and each age group is assigned an expected value of life given the expected years of life remaining to them. This method places a relatively low value on elderly people who make up a large proportion of the population affected by air pollution. Our second estimate relies on the assumptions adopted by the USEPA : an additional  $\left(\frac{1}{10,000}\right)$  chance of death is worth \$600 per year and the USEPA places the same value on mortality risks faced by populations of all ages. The USEPA assumptions lead to much higher damages. A number of other impacts of air pollution are also captured by APEEP including impaired visibility, increased rates of illnesses, reduced recreation services, lost timber yields, and decreased agriculture harvests (Muller and Mendelsohn, 2007).

For a small sample of individual sources, APEEP is used to plot estimates of the empirical marginal damage function for emissions of  $SO_2$ . This experiment is intended to examine the slope of the marginal

damage function at the source level. Computing the marginal damage function for a specific source entails the following procedure. For SO<sub>2</sub>, first the model computes total SO<sub>2</sub> damages with the selected source emitting zeros tons and all other SO<sub>2</sub> sources emitting at their baseline levels. The model then computes total SO<sub>2</sub> damages. Next, one ton is added to the selected source again with all other sources of SO<sub>2</sub> emitting at their baseline levels. The difference in SO<sub>2</sub> damages between the zero emission case and the add-one-ton case is the marginal damage of emitting the first ton of SO<sub>2</sub> from this particular source. (For each of the remaining iterations, all other sources of SO<sub>2</sub> emit at their baseline levels). Next, APEEP adds another ton of SO<sub>2</sub> to the selected source and determines the difference in damages between the add-one-ton and the add-two-tons scenarios. This experimental procedure is repeated up to 10,000 tons of emissions for each source. This experiment is conducted at a source in a large urban area, a source in a small urban area, and at a rural power plant. This experiment is conducted at a source in a large urban area, a source in a small urban area, and at a rural power plant.

## IV. Marginal Damage Results

In this study we have computed marginal damages from both ground level sources and point sources. Table 1 reports the marginal damages corresponding to emissions from ground-level sources of the six pollutants tracked by APEEP. Ground level sources include vehicles, residences, and commercial facilities without a smokestack. Emissions of ammonia (NH<sub>3</sub>), sulfur dioxide (SO<sub>2</sub>), and fine particulates (PM<sub>2.5</sub>) yield the greatest marginal damage for sources at the 50<sup>th</sup> percentile: \$980, \$1,030, and \$1,450, respectively. Emissions of PM<sub>10</sub>, NO<sub>x</sub>, and VOC are much less harmful: the marginal damages due to emissions from 50<sup>th</sup> percentile sources for these pollutants are closer to \$200. Table 1 indicates that across the U.S., the marginal damages from ground sources are quite variable. The distribution of ammonia and PM<sub>2.5</sub> sources show the greatest range between the highest and lowest marginal damages. The range for PM<sub>2.5</sub> between the 1<sup>st</sup> percentile and the 99.9<sup>th</sup> percentile emission source is nearly \$53,000. Note that with all pollutants, the distribution of marginal damages is right-skewed. The marginal damages of the 99<sup>th</sup> percentile source minus the 50<sup>th</sup> percentile source is larger than the difference between the 50<sup>th</sup> percentile source and the 1<sup>st</sup> percentile source.

Figure 1 shows the distributions of PM<sub>2.5</sub>, NO<sub>x</sub>, and SO<sub>2</sub> marginal damages for ground sources in a stacked histogram. The red-colored bars correspond to the distribution of PM<sub>2.5</sub>, the yellow-colored bars correspond to the distribution of SO<sub>2</sub>, and the blue bars correspond to NO<sub>x</sub>. Figure 1 indicates that the NO<sub>x</sub> distribution is much less variable than either PM<sub>2.5</sub> or SO<sub>2</sub>: most of the mass in the NO<sub>x</sub> distribution lies near the 50<sup>th</sup> percentile source, at \$220/ton. In contrast, SO<sub>2</sub> and (especially) PM<sub>2.5</sub> are right-skewed

with a long tail<sup>3</sup>.

Figures 2 and 3 display how marginal damages of emissions of PM<sub>2.5</sub> and SO<sub>2</sub> from ground-level sources are distributed across space. The maps capture the marginal damages due to emissions from ground sources in each county in the contiguous U.S. Figures 2 and 3 reveal that the most harmful emissions are generated by sources that are located in large cities. Emissions of PM<sub>2.5</sub> from Los Angeles, Chicago, Atlanta, Washington D.C., San Francisco and the New York metropolitan area have the largest marginal damages (these areas are represented in black). Sources of SO<sub>2</sub> show a similar pattern: sources in Los Angeles, San Diego and New York are in the top damage category. Figures 2 and 3 also reveal that there are many rural counties with relatively low marginal damages (shown in green) and comparatively few urban counties with high marginal damages. The urban counties on the maps are the outliers in the right-hand tail of the distributions in figure 1. Hence, the maps are consistent with the right-skewed nature of the distributions revealed by Table 1 and Figure 1.

Table 2 utilizes the marginal damage estimates in table 1 to calculate the trading ratios (fixed exchange rates equal to the inverse ratio of marginal damages) for selected sources of NO<sub>x</sub>, SO<sub>2</sub>, and PM<sub>2.5</sub>. For example, a source at the 25<sup>th</sup> percentile must acquire two tons of SO<sub>2</sub> allowances from a source at the 1<sup>st</sup> percentile in order to emit an additional ton of SO<sub>2</sub>. Similarly, a source at the 50<sup>th</sup> percentile must acquire 11 tons of allowances of NO<sub>x</sub> from a source in the 1<sup>st</sup> percentile to discharge one more ton of NO<sub>x</sub>. The trading ratios between sources at the 25<sup>th</sup> percentile and sources at the 1<sup>st</sup> percentile in table 2 range from 2:1 to 5:1. Trading ratios between the 1<sup>st</sup> percentile and the 50<sup>th</sup> and 75<sup>th</sup> percentile range between 5:1 and 24:1. Finally, trading between the 1<sup>st</sup> percentile and the 99.9<sup>th</sup> percentile require ratios between 63:1 and 176:1.

The maps in Figures 2 and 3 provide a clearer image of how these trades break down across the landscape. Sources in the lower percentiles of the distribution are mostly in rural areas such as the Rocky Mountain and Great Plains states. Sources with average marginal damages are found in suburban and small urban areas and sources whose emissions produce the highest marginal damages are located in the largest cities in the country. Therefore, the largest trading ratios are between rural sources and sources located in cities such as New York and Los Angeles. These large exchange rates (between 63:1 and 176:1) reflect the higher value of abatement in cities, due to the large avoided damages, relative to the lower value of abatement in rural (low damage) areas. The high trading ratios between urban and rural sources would encourage substantially more abatement in the metropolitan areas. Whether there will be an accumulation of emissions in rural areas depends largely upon the optimal aggregate emission levels. While these ratios imply shifting pollution from cities to rural areas, stricter aggregate limits on emissions would limit the relative migration of pollution

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<sup>3</sup>The distributions shown in figure are truncated at \$10,000 in order to reveal the variability in the lower range of the x-axis.

towards rural areas that these ratios suggest should occur.

Large trading ratios between sources do not necessarily imply large distances between sources. Sources that are physically located close to one another may have very different marginal damages. Returning to Figures 2 and 3, it is obvious that emissions in the largest metropolitan areas are several times more harmful than emissions in neighboring suburban and rural counties. For example, ground-level emissions of  $\text{PM}_{2.5}$  in Chicago generate damages of \$23,000/ton yet an equivalent emission in nearby Kankakee County, Illinois produces damages of \$5,200/ton. The distance between these counties is just 35 miles.

In Table 3, we present evidence of the importance of stack height in determining the marginal damage of emissions. The marginal damages corresponding to  $\text{PM}_{2.5}$  and  $\text{SO}_2$  emissions from a ground level source in New York City, Washington, D.C., Atlanta, and Houston are compared to nearby (high stack) emissions of  $\text{PM}_{2.5}$  and  $\text{SO}_2$  from actual power plants. In each case, the marginal damage of ground level emissions in the metropolitan area are matched to emissions of the same pollutant at the nearby power plant. In addition to the trading ratio between the ground-level source and the power plant's emissions, the stack height and name of each selected power plant is reported in table 3. The damage resulting from an emission of one ton of  $\text{PM}_{2.5}$  at ground level in New York City is equal to eleven tons of  $\text{PM}_{2.5}$  emissions from Con Edison's 74<sup>th</sup> Street Station (in New York City). The damages from eight tons of  $\text{SO}_2$  from the power plant is equal to the damage caused by one ton of  $\text{SO}_2$  discharged at ground level. The 495 foot stack at the power plant disperses the pollution away from New York City so that fewer people are ultimately exposed to the pollution. The mitigating effect of stack height on marginal damages is evident in each of the simulations reported in Table 3. The trading ratios imply that ground-level emissions of  $\text{PM}_{2.5}$  are between 11 and 23 times more harmful than equivalent emissions from the urban power plants. (Ground-level emissions of  $\text{SO}_2$  are 7 to 10 times more harmful than power plant emissions.) High stacks are an extremely effective abatement device for emissions in urban areas because the tall stack substantially reduces total exposures (and marginal damages) relative to ground-level emissions.

It is important to recognize that the magnitude of the marginal damage estimates is sensitive to a number of contentious parameters in the integrated assessment model. Specifically, marginal damages are sensitive to the value attributed pollution-related mortality and whether the value changes according to the age of the exposed population (Muller and Mendelsohn, 2007). Since these assumptions affect the level of the marginal damages and, in turn, the aggregate cap on emissions, there is likely to be controversy associated with selecting these values when a differentiated permit regime is first established. However, these particular assumptions do not affect the exchange rates between sources because the exchange rates are based primarily on air transport of emissions and the proximity of each source to urban areas. Table 4 compares the trading ratios among ground sources of  $\text{PM}_{2.5}$  using three different assumptions related to the value of mortalities.

The second column reports the trading ratios from table 2 using the relatively conservative assumptions embodied in the initial settings of APEEP. The third column shows the ratios that emerge when we apply the same value to all mortalities regardless of the age of the population. The fourth column displays the ratios resulting from the USEPA’s approach (USEPA, 1999) to valuing mortalities<sup>4</sup>. Table 4 shows that the trading ratios are minimally affected by this range of assumptions. Hence, although the assumptions in the integrated assessment model will affect the optimal aggregate cap (by changing the expected marginal damage), they have virtually no effect on the relative value of pollution across sources.

In addition to computing the marginal damage at each source, we also estimate the marginal damage function for SO<sub>2</sub> at individual sources. That is, we compute the marginal damage for each ton across a wide range of emissions: from 1 ton to 10,000 tons emitted at a single site. This experiment focuses on four sites: ground level emissions in New York City (a large city), ground level emissions in Nashville, Tennessee (a small city), and ground and tall stack emissions from the Tennessee Valley Authority’s Johnsonville Power Plant (a large, rural point source). Figure 4 displays the marginal damage function for these four sources of SO<sub>2</sub>. The results reveal that marginal damages are effectively constant for a single source (total damages are linear). That is, the marginal damage functions are essentially flat. The intuitive reason for this result is that the pollution from a single source is distributed widely across space. One source causes a very small increase in ambient concentrations at each location. Marginal damages consequently do not change with the level of emissions by a single source because additional emissions by any one firm do not appreciably change the ambient concentrations. Figure 4 does suggest, however, that there is considerable variability in the level of marginal damages across sources: the SO<sub>2</sub> emission in New York City is eight-times more harmful than the SO<sub>2</sub> emissions from the Johnsonville Power Plant.

## V. Case Study of Sulfur Dioxide Trading

In order to demonstrate the welfare gain from efficient versus cost effective regulatory policies, we present a case study of the power plants in the SO<sub>2</sub> permit trading program established under Title IV of the 1990 Clean Air Act Amendments (CAAA). The 660 electric generating units in this sample emitted more than 80% of the total emissions of SO<sub>2</sub> permitted under Title IV. Hence, this experiment captures the sources that discharged the bulk of the SO<sub>2</sub> emissions regulated by Title IV. The trading regime in Title IV is credited with cost-savings, relative to the previous command and control approach, of approximately \$150 million per year (Keohane, 2006). Our experiment examines the additional welfare gain that would occur if

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<sup>4</sup>In the first perturbation, labeled fixed VSL, we use the same value of mortality (\$2 million) as in the base case. The difference is that all mortalities receive equal value regardless of age. In the USEPA method, we employ a \$6 million value for mortality (the agency’s preferred value) and APEEP applies that value uniformly to the exposed population.



regulatory policies moved from the current, cost-effective trading program to an efficient trading regime.

As discussed in section II, there are two sources of welfare gain from moving to an efficient trading program. First, the regulator can determine an optimal aggregate emission cap or aggregate level of damages for the undifferentiated permit system. In our first simulation, we determine the optimal cap and the corresponding welfare gain relative to the cap that was set in 2002. Second, the regulator can allocate emissions (abatement) across sources so that marginal damage is equated to marginal abatement cost at each source. Accordingly, in the second simulation, we develop the efficient trading ratios across firms and compute the associated welfare gain. This second experiment measures the benefit of implementing the efficient allocation.

In this case study, we use a functional form for the abatement cost function that best fits the observed abatement cost data gathered from these coal-fired power plants (Keohane, 2006). We rely on a constant elasticity form.

$$MC_i = (\alpha_1 + \delta_i) E_i^{\alpha_2} \tag{20}$$

Each firm faces the same elasticity parameter ( $\alpha_2$ ) and the same base intercept parameter ( $\alpha_1$ ). But each firm also has a firm-specific shift parameter ( $\delta_i$ ) that allows for heterogeneity in costs across firms. Heterogeneity in firms' marginal costs may be due to differences in abatement technology employed by firms or firm-specific opportunities for substituting inputs in production processes. We assume that:  $E(\delta) = 0$ , and  $E(\delta^2) = \sigma_c$  (where E is the expectation operator).

The first step toward an empirical estimate of the firms' marginal abatement cost function is the derivation of the elasticity parameter ( $\alpha_2$ ). We rely on marginal abatement cost data for SO<sub>2</sub> (Keohane, 2006). The parameter estimate for ( $\alpha_2$ ) is generated in a log-log regression of marginal abatement costs on tonnage of emissions. We produce three estimates of ( $\alpha_2$ ): a global estimate corresponding to the entire aggregate cost schedule, an alternative estimate based on the aggregate cost schedule above 3 million tons, and a third estimate above 4 million tons. The three resulting estimates of ( $\alpha_2$ ) are: -1.2, -1.7, and -2.9. We test the sensitivity of firm behavior in the simulations to the elasticity parameter ( $\alpha_2$ ) by repeating the simulations for each value of ( $\alpha_2$ ). Note that because (20) is an inverse cost function, the price elasticity is  $(1/\alpha_2)$ .

The next step is to identify  $(\alpha_1 + \delta_i)$ , the source-specific intercept term. To accomplish this we rely on the fact that each electric generating unit in this analysis was regulated under the SO<sub>2</sub> permit trading program in 2002 (the year in which the integrated assessment model is calibrated). In that year, each firm faced a permit price of \$175 (USEPA, 2007a). Based on the fact that profit-maximizing behavior induces firms to

equate their marginal abatement costs to the permit price, we assume that the marginal cost of each firm was equal to \$175 in 2002. With the left-hand side of (20) equal to \$175, and with source-specific emissions ( $E_i$ ) provided by the USEPA (USEPA, 2006), we can solve for  $(\alpha_1 + \delta_i)$  using the following formula<sup>5</sup>:

$$(\alpha_1 + \delta_i) = \left( \frac{175}{E_i^{\alpha_2}} \right). \quad (21)$$

In order to identify a functional form for the marginal damage function, we rely on the results shown in figure 4 that indicate the marginal damage function for each individual source is flat. This yields a constant marginal damage function of the form:

$$MD_i = (\beta_1 + \theta_i). \quad (22)$$

The shift parameter ( $\theta_i$ ) in the  $(\beta_1 + \theta_i)$  term captures firm-specific marginal damages. We assume the following properties regarding the distribution of the ( $\theta$ ) parameter:  $E(\theta) = 0$  and  $E(\theta^2) = \sigma_d$ . As reported in section IV, heterogeneity in the damages of firms' emissions may be due to the location of firms (urban versus rural settings) as well as source specifications (ground-level emissions versus tall smokestacks). Estimates of (22) for each source are produced using the APEEP integrated assessment model through the algorithm outlined in section III.

The first simulation calculates the optimal aggregate cap for the 660 generating units. The aggregate level of SO<sub>2</sub> emissions in 2002 that led to the price of \$175/ton was 7.75 million tons. The optimal aggregate cap should equate expected marginal cost with expected marginal damage. Using the marginal damages calculated in the previous section<sup>6</sup> for each of the 660 power plants, we find that the expected marginal damage of the 660 electric generating units is \$900/ton. The aggregate level of emissions required to increase prices to \$900 is shown in the row of table 5 that is labeled, cost-effective: (P = \$900). When  $\alpha_2 = -2.9$ , optimal aggregate emissions are 4.41 million tons, with  $\alpha_2 = -1.7$ , aggregate emissions fall to 2.87 million tons, and with  $\alpha_2 = -1.2$ , aggregate emissions fall to 2.04 million tons. The greater the elasticity ( $1/\alpha_2$ ) of the marginal cost function, the greater the change in emissions. The results of this simulation suggest that the optimal aggregate level of emissions for these 660 electric generating units should have been between 40 percent to 70 percent lower than the 7.75 million tons that were emitted in 2002.

<sup>5</sup> Given that  $E(\delta) = 0$ , it follows that  $\alpha_1 = \left( \frac{175}{E_m^{\alpha_2}} \right)$  where  $E_m$  is the expected value of emissions in the sample of 660 power plants.

<sup>6</sup> These marginal damage estimates reflect the relatively conservative approach to modeling mortality risks and valuation.

The welfare gain associated with moving to the optimal aggregate cap can be calculated using the formula shown in equation (18). The calculation assumes the regulator is still using undifferentiated permits, firms face a uniform permit price, but with the optimal aggregate cap and the resulting permit price of \$900. The welfare effect of the different levels of emissions are shown in parentheses in table 5. With  $\alpha_2 = -2.9$ , the welfare gain (relative to the policy in 2002 that yielded emissions of 7.75 million tons) of implementing the optimal cap is \$1.83 billion, with  $\alpha_2 = -1.7$ , the welfare gain is \$2.75 billion, and with  $\alpha_2 = -1.2$ , the welfare gain is \$3.29 billion annually. Firms reduce their emissions more dramatically with the more elastic cost function yielding larger welfare gains. Note that the welfare gains associated with using the conservative optimal aggregate cap are more than an order of magnitude greater than the cost-savings due to moving from standards to tradeable permits that is reported in the literature (Keohane, 2006).

The second simulation explores moving from undifferentiated permits to a system of differentiated permits with the fixed trading ratios explored in section II. We model each firm's emissions after trading: each firm equates their marginal costs to their marginal damages. As shown in the row labeled "efficient trading base" in Table 5, aggregate emissions change slightly when moving from the cost-effective regime (with prices = \$900) to an efficient differentiated permit system. Specifically, for each value of ( $\alpha_2$ ) emissions are slightly higher when firms equate marginal costs to marginal damages than when firms equate their marginal costs to the expected marginal damage. For example, with  $\alpha_2 = -1.2$ , the differentiated permit system calls for aggregate emissions of 2.22 million tons, in contrast to the 2.04 million tons dictated by the undifferentiated permit system. The slight increase in total emissions for all values of ( $\alpha_2$ ) reflects trades from power plants that have high marginal damages to plants with low marginal damages. Due to the exchange rates and the constant elasticity form of the cost function, low damage power plants increase their tonnage more than high damage power plants decrease tonnage.

As discussed in section II, these trades do not increase aggregate damages even though they increase tonnage. However, the trades do reduce overall costs. Table 5 also measures the increase in total welfare (shown in the parentheses). The welfare gain from allocating permits efficiently across firms is equal to \$100 million, annually. The welfare gain is computed using the formula in equation (18), and it is insensitive to the value of the elasticity parameter ( $\alpha_2$ ). The benefits strictly due to the efficient allocation are relatively small compared to the gain generated by implementing the optimal aggregate cap because the abatement cost function is very steep in this example. Although these power plants have a wide range of marginal damages, suggesting potentially large gains from trade, the power plants do not make dramatic changes in emissions in response to the damage-differentiated permits because of the steep cost function. Consequently the welfare gains are relatively small. However, these gains are not insignificant when compared to the annual cost savings of \$150 million associated with moving from standards to the current system of tradeable permits.

The welfare gain due to using differentiated permits is due to variation in the marginal damages across the power plants in the sample. To show this variability, figure 5 maps the values of  $(\theta_i)$  for each plant: the demeaned marginal damages for SO<sub>2</sub>. The value of  $(\theta_i)$  is negative if the unit's marginal damage is below the mean of \$900 and  $(\theta_i)$  is positive if the marginal damage is above the mean. Most of the facilities west of the Mississippi River and in rural areas of the deep south show negative values (green) of  $(\theta_i)$ . Many plants in the Midwest have near zero values (yellow): their marginal damages are close to the average marginal damage of the sample. Conversely, many of the plants in the urban Midwest and in the east show large positive values (orange and dark red) of  $(\theta_i)$ . The figure implies that the electric generating units bearing orange and especially red dots would reduce their emissions under a differentiated permit policy because of their relatively high marginal damages. The plants with the yellow dots would choose emissions close to the cost effective level (with a permit price of \$900). However, the units bearing green dots would choose emissions that are greater than the cost effective solution at \$900 due to their relatively low marginal damages. Thus, with marginal damage-differentiated permits, SO<sub>2</sub> emissions for electric generating units would increase in the west and rural areas and fall in the urban Midwest and in the east. It is important to note that using the marginal damages to set the aggregate emission cap will likely reduce emissions at all sources since the 2002 permit price of \$175 was so much lower than the expected marginal damage of \$900. However, figure 5 implies that sources with positive values of  $(\theta_i)$  would do more abatement than those sources with negative  $(\theta_i)$ .

In order to understand the importance of some of the key assumptions in the APEEP model, we reproduce the case study using the USEPA assumptions about the value of premature mortality. This approach entails a \$6 million value of a statistical life and this value is applied uniformly to populations of all ages. The bottom two rows in table 5 display the tonnage of emissions and the corresponding welfare gain from a cost-effective policy when the expected marginal damage is \$3,900 (reflecting USPEA's approach) and from the efficient policy (also reflecting the marginal damages computed using USEPA's assumptions). Intuitively, since the cost functions have not changed, the higher damages imply more severe emission reductions as well as greater welfare gains. The emission reductions range from 66 percent with the most inelastic marginal cost function to 92 percent when the elasticity parameter is set to (-1.2). The welfare gain stemming from the cost-effective policy (P=\$3,900) ranges from \$17 billion to nearly \$26 billion, annually. The welfare gain resulting from efficient trading is also greater due to the larger marginal damage estimates: for each value of the elasticity parameter in the marginal cost function the additional gain is \$200 million, annually.

## VI. Conclusions

This paper argues that there is a tremendous potential welfare gain from moving from cost effective to efficient pollution regulations. This final step in the evolution of market-based environmental regulations requires that the regulator knows the marginal damages. The paper consequently provides initial estimates of the marginal damages of air pollution emissions for 10,000 sources in the U.S. Armed with these marginal damages, the regulator can set optimal aggregate emission caps (or optimal aggregate damages) that equate expected marginal cost to expected marginal damage. Further, differentiated permits can be instituted that equate the marginal damage at each source with its marginal cost of abatement. The potential welfare gains from making these improvements are an order of magnitude larger than the reported gains associated with moving from standards to cost effective undifferentiated tradeable permits. The sheer size of these benefits makes a strong case for a new generation of market-based pollution regulations that utilizes these newly available marginal damages estimates.

A general theme of this paper is that efficient policy focuses on damages not on tonnage. Regulations need to give a higher priority to removing tonnage in high damage locations. The marginal damage of emissions in especially large metropolitan areas are much higher than in rural areas: marginal damages corresponding to ground sources in the nation's largest cities are over 150 times greater than the damages generated by emissions in rural areas. Efficient policy requires a substantial increase in abatement in urban and especially metropolitan areas. In our case study, for example, the efficient policy called for a large increase in SO<sub>2</sub> abatement in the eastern U.S. Another important finding is that ground level sources are far more dangerous than point sources with tall smokestacks especially in large cities. Ground level emissions lead to much higher human exposures. Given the relatively low cost of tall stacks, the results suggest that constructing tall smokestacks in urban areas is an effective abatement strategy.

There are still some critical and controversial steps that must be taken in order to move from this analysis to the implementation of new laws and policies. First, regulators must choose specific values for the health effects of air pollution. Air pollution causes increased mortality rates, chronic illness, and minor health symptoms. A range of values are now assigned to these consequences by different public agencies. As we have shown these values are critical to determining society's aggregate abatement goals. Second, regulators need to decide whether to assign a single value of health effects to all age groups or to ascribe different values for each age cohort. Because the elderly have lower expected remaining lifetimes than younger age groups, a case can be made to assign lower values to elderly mortality risks. On the other hand, the constitution guarantees equal treatment of all citizens. If an agency differentiates by age, should they also differentiate these values by income, gender, and race? Third, although the public health literature consistently finds

a relationship between air pollution and mortality rates, different studies suggest very different degrees of sensitivity. Regulators must choose a value from this range of results.

The optimal aggregate cap for each pollutant is quite sensitive to these controversial issues. Higher values of human health, greater sensitivity of mortality rates to exposures to pollution, and equal mortality values for all age groups lead to lower aggregate caps and higher permit prices. The relative damage caused by emissions from different sources, however, is not sensitive to these controversial issues. Relative damages across firms depend primarily on the transport of pollutants and the proximity of source to human populations. Therefore, the spatial allocation of emissions under an efficient trading program is insensitive to the assumptions regarding health responses and valuation.

The paper demonstrates that calculating the marginal damages for a large number of air pollution sources is possible and practical. Using an integrated assessment model, marginal damage values are calculated for 10,000 sources of air pollution in the U.S. for six pollutants. These calculated values are now available to every firm, regulator, and researcher in the U.S. (website citation forthcoming). Regulators and researchers can use the marginal damages to determine whether they should encourage abatement at urban versus rural sources or ground level versus high stack sources in a particular region. Firms curious about how to allocate abatement at individual facilities may use this data. Investors concerned about the pollution damages associated with different companies can calculate the harm caused by each company's facilities.

This paper computes the welfare gain of implementing an efficient regulatory structure for a sample of coal-fired power plants. Society has much to gain by implementing a new generation of efficient regulations more broadly. The methodology used in the paper could be applied to other sources of air pollution and to other pollutants such as water pollution, solid waste, and hazardous waste. An entirely new generation of efficient regulations is ready to be developed as soon as marginal damage estimates can be created and incorporated into policy.

Figure 1: Distribution of Marginal Damages

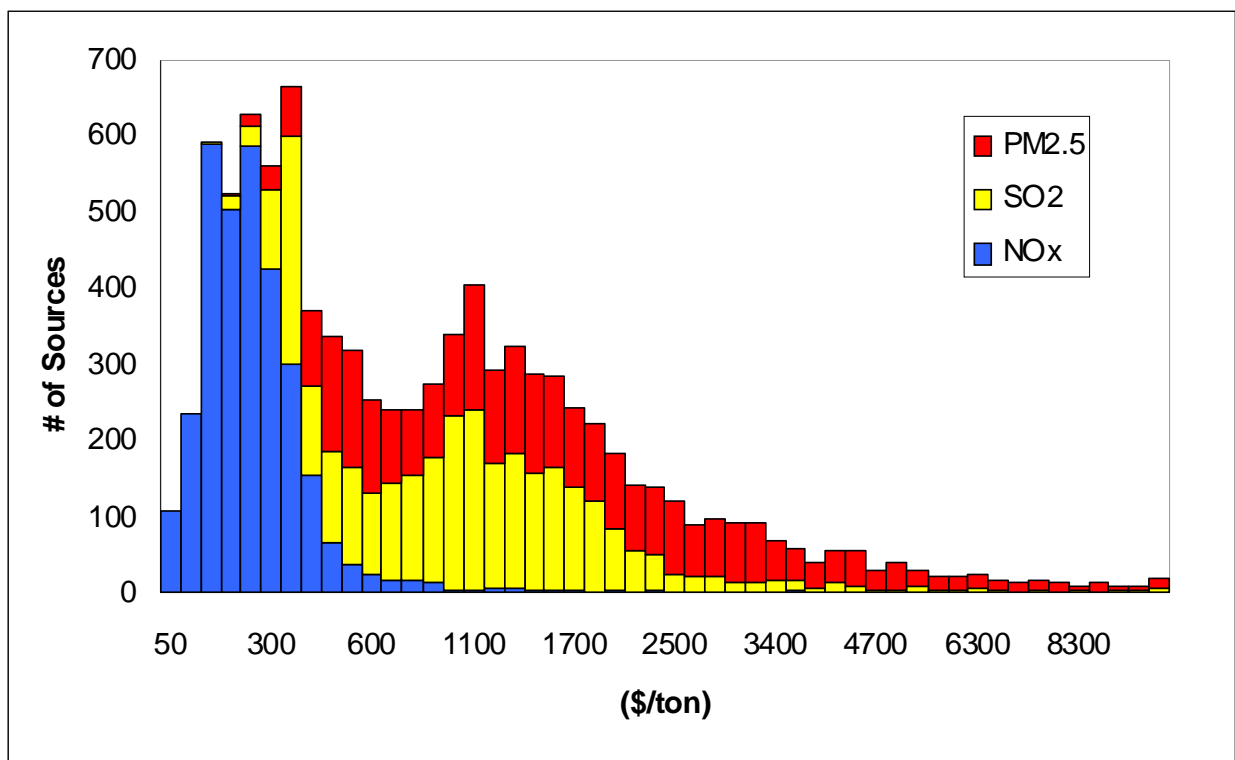


Figure 2: Marginal Damages of PM<sub>2.5</sub> Emissions from Ground Level Sources (\$/ton/year).

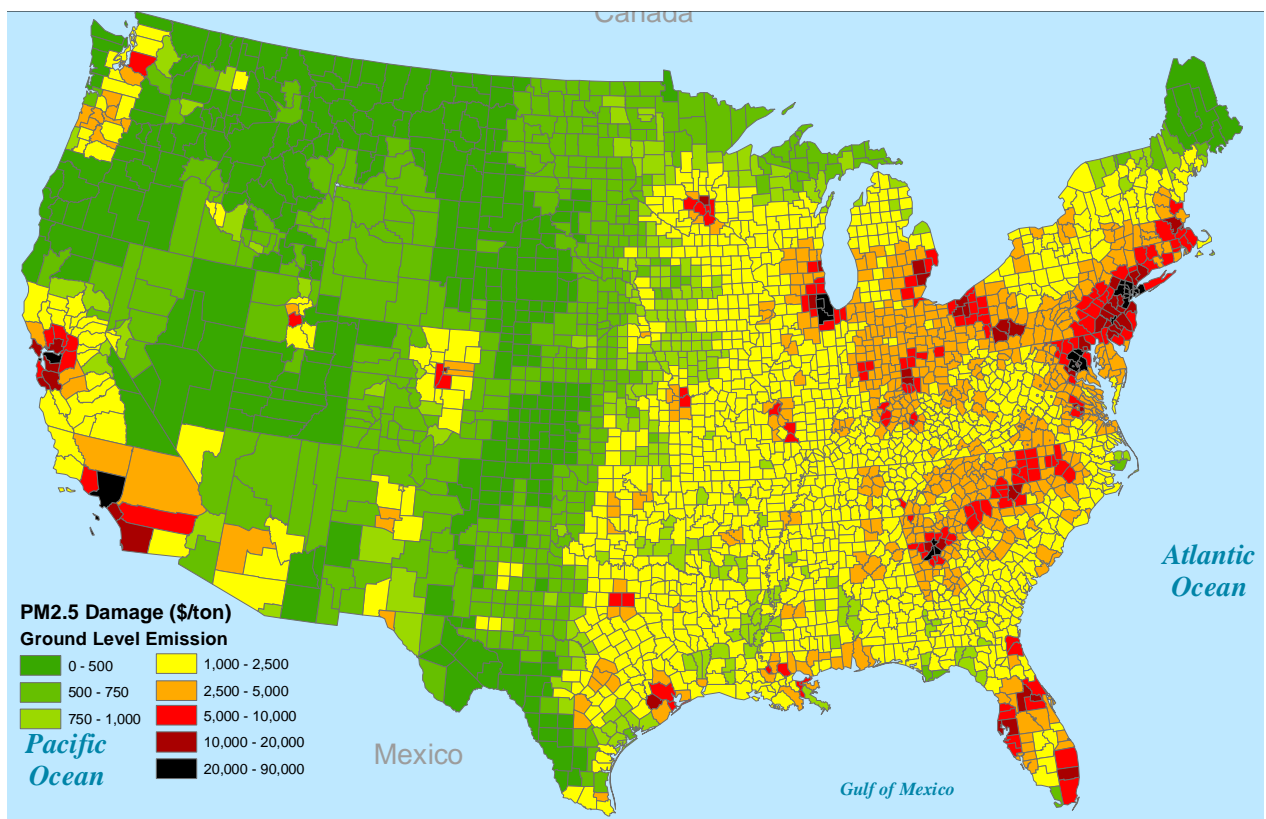




Figure 3: Marginal Damages of SO<sub>2</sub> Emissions from Ground Level Sources (\$/ton/year).

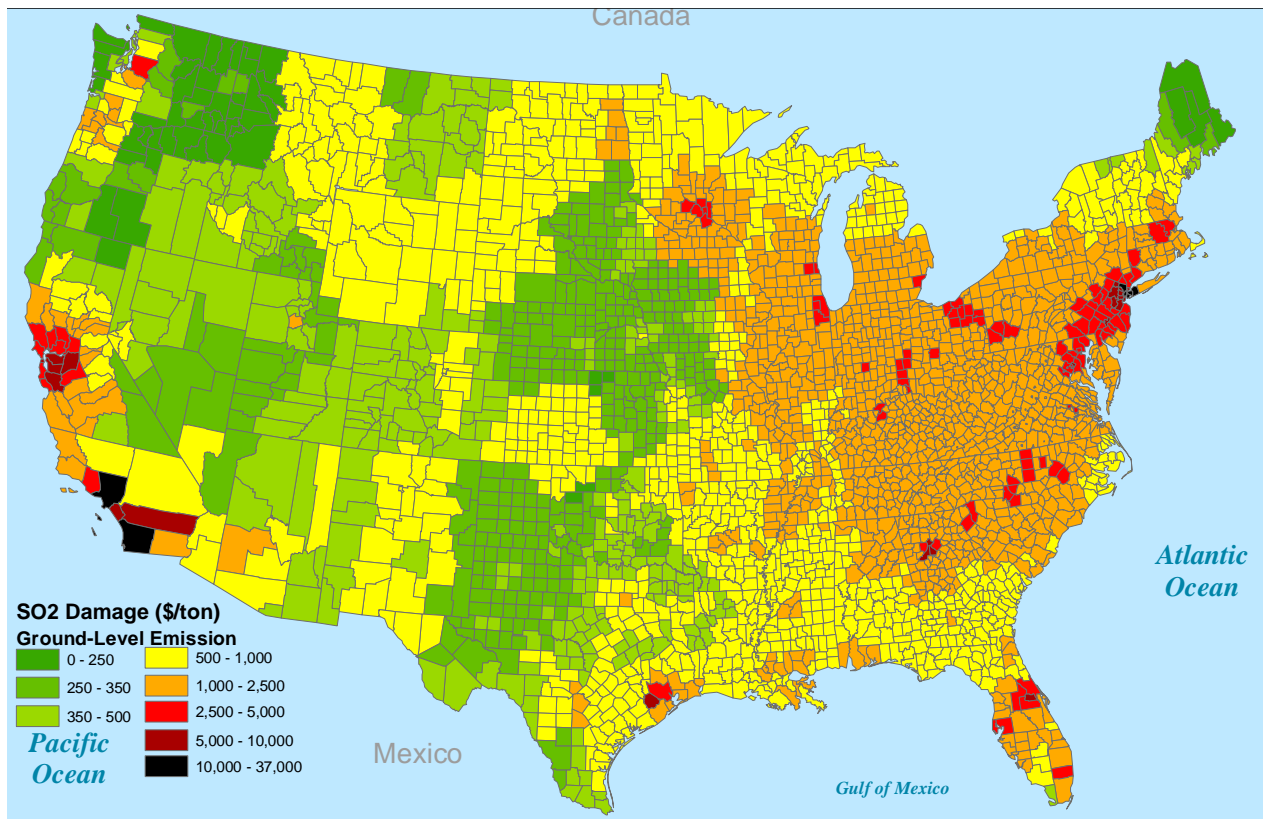


Figure 4: Marginal Damage for SO<sub>2</sub> Emissions

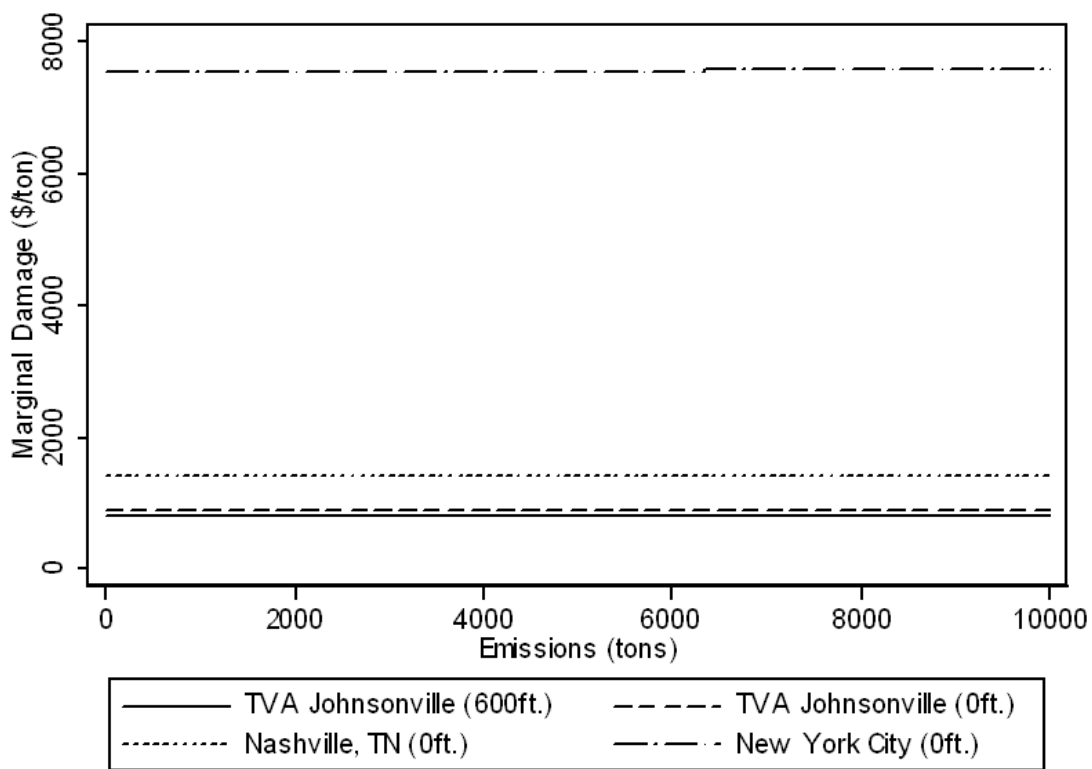


Figure 5: Demeaned SO<sub>2</sub> Marginal Damages.

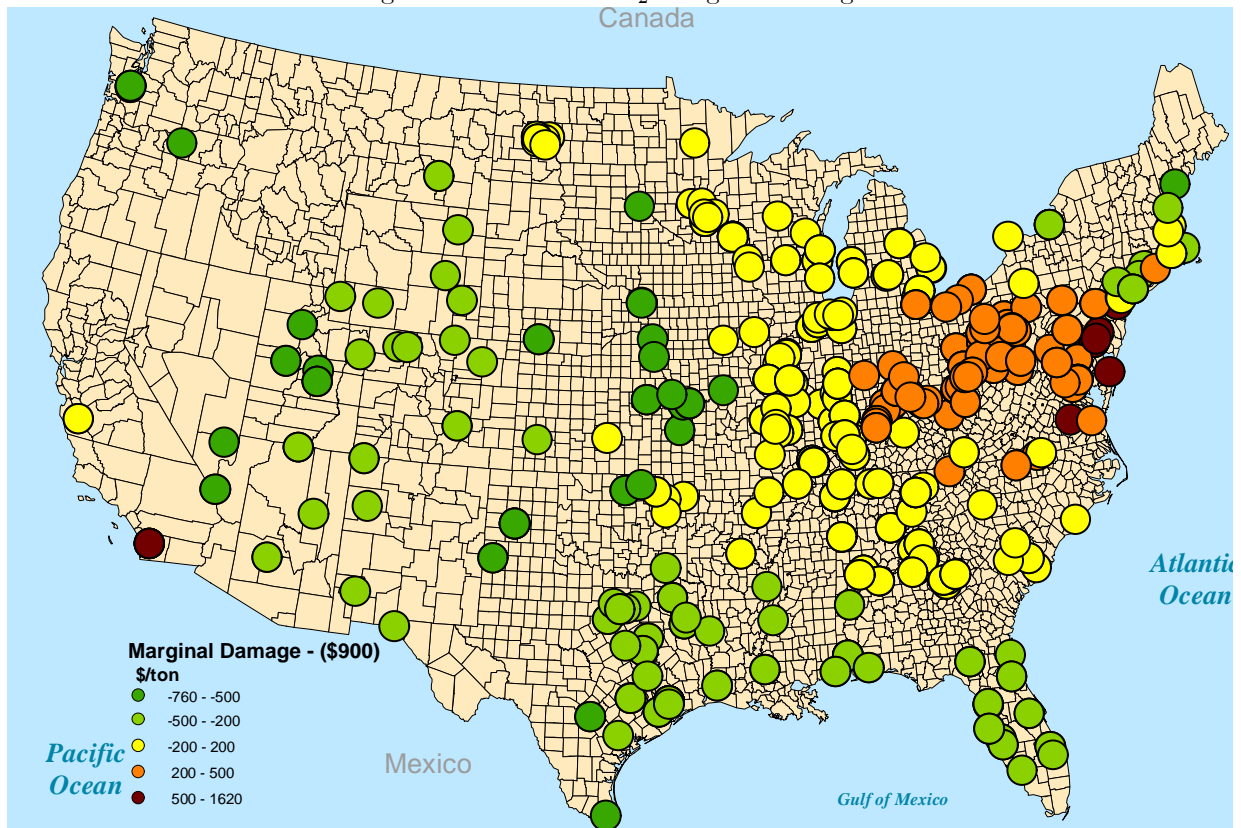


Table 1: Marginal Damage for Ground Sources (\$/ton/year)

Pollutant	1 <sup>st</sup> %	25 <sup>th</sup> %	50 <sup>th</sup> %	75 <sup>th</sup> %	99 <sup>th</sup> %	99.9 <sup>th</sup> %
PM <sub>2.5</sub>	300	800	1,450	2,600	19,400	52,900
PM <sub>10</sub>	70	140	210	370	2,740	8,900
NO <sub>x</sub>	30	130	220	310	1,150	2,440
NH <sub>3</sub>	90	300	980	2,600	28,600	87,200
VOC	30	90	150	270	1,980	5,600
SO <sub>2</sub>	230	570	1,030	1,490	5,300	14,400

Table 2: Trading Ratios for Ground Sources

Quantiles	SO <sub>2</sub>	NO <sub>x</sub>	PM <sub>2.5</sub>
25 <sup>th</sup> :1 <sup>st</sup>	2:1	5:1	2:1
50 <sup>th</sup> :1 <sup>st</sup>	5:1	11:1	6:1
75 <sup>th</sup> :1 <sup>st</sup>	12:1	24:1	24:1
99 <sup>th</sup> :1 <sup>st</sup>	46:1	90:1	132:1
99.9 <sup>th</sup> :1 <sup>st</sup>	63:1	81:1	176:1

Table 3: Trading Ratios for Urban Ground Sources and Power Plants

Urban Ground Source City, State	Nearby Power Plant Firm, Facility	Stack Height (ft.)	Trading PM <sub>2.5</sub>	Ratios SO <sub>2</sub>
New York, NY	Con. Edison, 74th Street Station	495	11:1	8:1
Washington D.C.	Potomac Power Resources, Benning	400	23:1	8:1
Atlanta, GA	Georgia Power Co., Jack McDonough	835	22:1	7:1
Houston, TX	Texas Genco, Inc., W.A. Parish	600	17:1	10:1

Table 4: Sensitivity Analysis: Trading Ratios for Area Sources of Fine Particulates

Trading Ratio	Base	Fixed VSL	USEPA
25 <sup>th</sup> :1 <sup>st</sup>	2:1	2:1	2:1
50 <sup>th</sup> :1 <sup>st</sup>	6:1	6:1	6:1
75 <sup>th</sup> :1 <sup>st</sup>	24:1	24:1	25:1
99 <sup>th</sup> :1 <sup>st</sup>	132:1	130:1	132:1

Table 5: Annual emissions of sulfur dioxide and welfare gains

Policy	$\alpha_2 = -2.9$	$\alpha_2 = -1.7$	$\alpha_2 = -1.2$
Current emissions: 7.75 million tons	million tons (\$billion)	million tons (\$billion)	million tons (\$billion)
Cost-Effective: (P = \$900)	4.41 (1.83)	2.87 (2.75)	2.04 (3.29)
Efficient Trading	4.49 (0.10)	3.01 (0.10)	2.22 (0.10)
Cost-Effective: (P = \$3,900)	2.58 (17.1)	1.19 (22.8)	0.54 (25.9)
Efficient Trading	2.66 (0.20)	1.27 (0.20)	0.61 (0.20)

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