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HETEROGENEOUS HARM VS. SPATIAL SPILLOVERS: ENVIRONMENTAL FEDERALISM AND US AIR POLLUTION

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ABSTRACT

The economics of environmental federalism identifies two book-end departures from the first-best, which equates marginal costs and benefits in all local jurisdictions. Local governments may respond to local conditions, but ignore inter-jurisdictional spillovers. Alternatively, central governments may internalize spillovers, but impose uniform regulations ignoring local hetero-geneity. We provide a simple model that demonstrates that the choice of policy depends crucial-ly on the shape of marginal abatement costs. If marginal costs are increasing and convex, then abatement cost elasticities will tend to be higher around the local policies. This increases the deadweight loss of those policies relative to the centralized policy, ceteris paribus.

Using a large simulation model, we then empirically explore the tradeoffs between local versus second-best uniform policies for US air pollution. We find that US states acting in their own interest lose about 31.5% of the potential first-best benefits, whereas the second-best uniform policy loses only 0.2% of benefits. The centralized policy outperforms the state policy for two reasons. First, inter-state spillovers are simply more important that inter-state hetero-geneity in this application. Second, welfare losses are especially small under the uniform policy because elasticities are much higher over the relevant range of the cost functions.

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1. Introduction

Environmental externalities typically take place within the context of a federation with several levels of government, as in the United States or the European Union. The relative efficiency of assigning regulation to different levels of government is a central question for environmental policy. A first-best policy would equate, in all locations, the marginal costs of abating pollution with marginal benefits, including spillovers into other jurisdictions. However, in practice this policy is unobtainable. Since the seminal work of Oates (1972), the fiscal federalism literature has emphasized two policies which depart from the first best in opposite ways, serving as book-ends.[1] On one hand, central governments are likely to impose a one-size-fits-all uniform policy that ignores local conditions. On the other hand, local jurisdictions can account for heterogeneity in benefits and costs, but they are likely to ignore inter-jurisdictional spillovers. Accordingly, the fiscal federalism literature has emphasized two factors when choosing the level of government at which to internalize externalities. The first factor is the degree of inter-jurisdictional spillovers: ceteris paribus, when spillovers are larger, the central government's policies will lead to higher welfare relative to local governments' policies. The second factor is heterogeneity: ceteris paribus, when inter-jurisdictional heterogeneity in benefits is larger, local governments' policies will lead to higher welfare relative to the central government's.

These trade-offs represent the Scylla and the Charybdis of environmental federalism. As Oates (2002a) summarized:

> [W]e are left with a choice between two alternatives: suboptimal local decisions on environmental quality or inefficient uniform national standards. And which of these two alternatives leads to a higher level of social welfare is, in principle, unclear. Empirical studies of these alternative regimes are needed to shed light on this issue. (p. 8)

This paper contributes to this literature in two ways. First, it introduces a new third factor, previously unnoticed, that plays an important role in the performance of different levels of government. In particular, we show that the more convex the supply of pollution abatement, the

[1] For more recent reviews, see Oates (1999, 2002a), Dalmazzone (2006), and Levinson (2003).

more centralized policies increase welfare relative to local policies. Second, illustrating the importance of all three factors, it fills the empirical gap highlighted in the above quotation, for arguably the most important environmental application facing developed economies over the last 50 years: ambient air pollution.

We begin with a simple model of pollution in a federation. The model includes heterogeneous marginal benefits of pollution abatement, inter-jurisdictional spillovers in benefits, and heterogeneity in the shapes of marginal abatement cost functions. Regulation involves setting pollution prices. The prices can be interpreted as Pigouvian taxes on pollution or, equivalently, because there is no uncertainty, they can be thought of as the price under a tradable pollution quota.

Analogous to the theory of optimal taxation, we show that the deadweight loss from errors in pollution prices, whether from ignoring inter-state spillovers or from ignoring heterogeneity, depends in part on the slopes of the marginal abatement cost curves over the region of the error. If they are highly inelastic, deadweight loss from errors in pollution prices will be small. This simple insight has an important—and to our knowledge previously unnoted—implication for environmental federalism. Simply put, if (1) the devolved policy involves the mistake of systematically *under*-pricing pollution (because of ignoring inter-jurisdictional policies); (2) the centralized policy involves the mistake of *noise* around the optimal prices (from imposing some average price); and (3) the marginal abatement cost functions (i.e. abatement supply functions) are increasing and convex in abatement (as we find empirically), then marginal abatement costs will tend to be more inelastic around the uniform policy. Other things equal, this tends to give the centralized policy an edge over devolved policies.[2]

The remainder of this paper is an empirical examination of these tradeoffs for the case of sulfur dioxide (SO_2) and nitrogen oxide (NO_x) pollution from the US electricity sector, the most important source of ambient air pollution in the United States. We use a detailed simulation model of the US electricity sector, together with models of pollution dispersions and damages, to compute three policies for regulating emissions. First, we find a reference policy, with fully

[2] We certainly do not claim that centralized policies will be better in all contexts. Clearly, if spillovers are low, so all benefits are essentially local, and heterogeneity in local benefits are substantial, then it is preferable to devolve authority to local jurisdictions.

differentiated state-level pollution prices that internalize all spillovers.[3] Second, we find the "optimal" policies from the perspective of each state acting under autarky. Finally, following Banzhaf et al. (2004), we also find the second-best uniform policy.

We find that that the reference policy yields substantial benefits over no control ($59.7 billion), consistent with the high benefit-cost ratios typically found for air pollution (Banzhaf et al. 2004, Muller and Mendelsohn 2007, US EPA 1999). The devolved policies lose 31.5% of those potential benefits. However, the second-best uniform policy loses only 0.2% of these benefits (still $114 million). Thus, the uniform policy approximates the first-best and far out-performs the state policies. This occurs for two reasons. First, most straightforwardly, inter-jurisdictional spillovers appear to be a bigger problem in this application than heterogeneous benefits. Yet the heterogeneity in benefits is not trivial: the inter-state range in the marginal benefits of abatement differ by a factor of 5.7. The second reason is that around the uniform policy, marginal abatement costs are quite inelastic, so the errors from ignoring the heterogeneity have little impact on over-all welfare. This is not true around the state policies. This is precisely the relationship we derive in our theoretical model.

In addition to our theoretical contributions, our empirical analysis is to our knowledge the first to consider *both* sides of the environmental federalism dilemma for a major policy. However, other recent papers have considered various aspects of centralized policies. Banzhaf et al. (2004) estimate the second-best uniform prices of SO_2 and NO_x, together with the resulting abatement, and find large welfare improvements from the status quo, but do not compare them either to the first-best case or to state policies. We follow their basic approach in this paper, extending it to these other policies.

Muller and Mendelsohn (2009) compare the relative welfare gains of switching from the *status quo* uniform price policy in the US (i.e. the acid rain trading program), which involves substantial under-abatement, to both a differentiated policy with the same aggregate emissions and to the first-best policy. They do not consider the second-best uniform price policy or the state policies. Thus, although both this paper and Muller and Mendelsohn (2009) cover similar ground, the two differ markedly in the questions they address. Muller and Mendelsohn consider

[3] We abstract from this issue of pre-existing taxes on capital on labor. In the context of those distortions, all the policies considered here would be second-best (Goulder et al. 1999, Parry 2005).

how the status quo price policies can be improved, looking at two margins, more differentiation (holding aggregate emissions at their sub-optimal level) versus more abatement (holding relative inter-jurisdictional prices constant at 1:1). We compare a policy devolving authority to local governments to a uniform policy, assuming optimization in each regime.

Others have considered regulations imposing a uniform ambient standard in each jurisdiction, rather than a uniform pollution price. Oates, Portney, and McGartland (1989) point out that, when these standards represent minimum environmental quality rather than a specific level, the costs of imposing this standard may not always be as high as one would expect. Nevertheless, they can be substantial. Dinan, Cropper, and Portney (1999) consider drinking water quality, a local public good with little or no spillover effects. In this case, local jurisdictions have an incentive to mandate the efficient level. Thus, the devolved policy is equivalent to the first-best. In contrast, the centralized uniform standard will be very inefficient. Since there are economies of scale in the reduction of pollutants in drinking water, small systems have higher cost per individual benefiting. Dinan et al. find that some households may lose up to $774 dollars per year from requiring the uniform regulation. Thus, centralized uniform regulation is less efficient than local control in this situation. See also Oates (2002b) for a discussion of similar issues related to arsenic in drinking water.

Implicit in our discussion are two hypotheses about the behavior of local jurisdictions. First, we assume they do internalize local benefits. This is the central finding of the environmental federalism literature (Oates and Schwab 1988). A long literature discusses potential departures from this central result under more general conditions, with the possibility of either a "race to the bottom" or a "race to the top" (Kunce and Shogren 2005; Levinson 2003; Markusen et al. 1995; Oates and Schwab 1988, 1996; Wellisch 1995). We abstract from these issues.

Second, we assume states ignore benefits or damages that accrue outside of their own borders. Empirical evidence seems to confirm this hypothesis. Helland and Whitford (2003) find that large polluting facilities in the US tend to be located in border counties, suggesting that states are less environmentally stringent when pollution is more likely to travel out of state. Sigman (2005) finds evidence that states ignore interstate spillovers in the case of water pollution. Similarly, Sigman (2007) finds that, internationally, nations with more decentralized governments have higher levels of regional (but not local) pollution. At the same time, however, List and Gerking (2000) find no evidence that Reagan's implementation of the "New Federalism," with its significant transfer of responsibility to state governments, had a negative effect on aggregate air emissions (see also Millimet 2003, Millimet and List 2003, and Fomby and Lin 2006). This may be because, especially at the time, federal policies already under-control, so it was not necessarily in states' interests to reduce enforcement.

2. Theoretical Model

We begin with a simple model of pollution in a federation. Pollution abatement A_i in each state $i = 1 \ldots N$ has constant marginal benefits within-state MB_{ii} and on other states j, MB_{ij}.[4] Marginal national benefits for abatement in state i are $MNB_i = \sum_j MB_{ij} \geq MB_{ii}$. Constant marginal benefits implies that within-state benefits are independent of inter-state spillovers and, hence, actions in other states. As discussed below, empirical evidence suggests that air pollution benefits are indeed approximately constant. In addition, each state has a marginal cost of abatement function $MC_i(A_i)$, with $MC'_i(A_i) \geq 0$. Inverting the marginal cost function gives the level of abatement associated with any price on pollution $A_i(t_i)$.

Policies involve choosing a vector of pollution prices $(t_1 \ldots t_N)$, such as through a Pigouvian tax or through a generalized cap-and-trade system.

2.1. First-Best Policy

The total potential gains from choosing a vector of pollution prices $(t_1 \ldots t_N)$ is

$$\sum_{i=1}^{N} \left[MNB_i * A_i(t_i) - \int_{0}^{A_i(t_i)} MC_i(x)dx \right]. \tag{1}$$

The first term is the gross benefits from the induced abatement in each state, equal to constant marginal benefits times abatement. The integral represents total abatement costs.

The first order conditions are:

$$MC_i(A_i) = MNB_i \ \forall \ i. \tag{2}$$

[4] We assume abatement benefits are spatially uniform within local jurisdictions. For purposes of the model, a "local jurisdiction" may be defined as that spatial scale at which this is so. Alternatively, this can be considered an approximation to first best.

Thus, the first-best policy simply equates marginal national benefits to marginal costs in each state. This could be accomplished by setting a Pigouvian tax t_i^* in each state equal to MNB_i. Alternatively, it could be accomplished by setting a national quota on pollution at the appropriate level and allowing inter-state trade at the ratios of marginal national benefits.

2.2. State Policies

The first departure from first-best that we consider is a policy in which authority is devolved to the states. From the perspective of each state *i*, total within-state benefits are:

$$MB_{ii} * A_i(t_i) + \sum_{j \neq i} MB_{ji} A_j(t_j) - \int_0^{A_i(t_i)} MC_i(x)\, dx. \tag{3}$$

Thus, the states equate their marginal within-state benefits to marginal costs:

$$MC_i(A_i) = MB_{ii} \; \forall \; i. \tag{4}$$

This allows for heterogeneity in the same way as the first-best policy, but departs from the first-best in ignoring inter-state spillovers. Since $MB_{ii} < MNB_i$, states under abate.

The approximate deadweight loss of the collective state policies, compared to the first-best policy, is given by:

$$DWL_s \approx \sum_{i=1}^{N} \frac{1}{2} (MNB_i - MB_{ii})^2 \frac{dA_i}{dt}, \tag{5}$$

where $\frac{dA_i}{dt}$ is the inverse of the slope of state *i*'s marginal abatement cost curve. Evidently, this loss shrinks to zero as $MB_{ii} \rightarrow MNB_i$. That is, if all pollution damages are captured within-state, there are no inter-jurisdictional spillovers for the central government to internalize and the state polices are equivalent to the first-best policy. It also shrinks as $\frac{dA_i}{dt} \rightarrow 0$. That is, as states' marginal abatement cost curves become steeper, given mistakes in pricing have smaller real effects on abatement.

2.3. Uniform Policy

In the second departure from the first-best that we consider, the federal government sets a single policy for the whole nation. In computing the optimal policy, the central government allows for inter-state spillovers, but is constrained to equate marginal costs in all states. For example, the central government may set a single uniform Pigouvian tax rate t_u; alternatively, it could set a national pollution cap with trading across states at a 1:1 ratio and yielding a pollution price of t_u.

The net benefits of this policy are

$$\sum_{i=1}^{N}\left[MNB_i * A_i(t_u) - \int_0^{A_i(t_u)} MC_i(x)dx\right]. \tag{6}$$

Taking first-order conditions with respect to t_u and recognizing that $MC_i(A_i(t_u))=t_u$ (that is, in all states firms equate marginal abatement costs to t_u), yields:

$$\sum_{i=1}^{N}(MNB_i - t_u)\frac{dA_i}{dt} = 0, \tag{7}$$

or,

$$t_u^* = \sum_{i=1}^{N} MNB_i \frac{dA_i/dt}{\sum_j dA_j/dt}. \tag{8}$$

That is, the second-best uniform price is a weighted average of each state's marginal national abatement benefits, where the weights are the relative slopes of the marginal abatement cost curves. States with inelastic marginal cost curves receive a low weight, because ignoring them causes little deadweight loss.

We can derive further insights into this case by considering a special kind of heterogeneity in the marginal cost curves, motivated by the economics of pollution abatement. Note first that we can focus on heterogeneity in the slopes of the marginal abatement cost function, for two reasons. First, as a practical matter firms choose a finite level of pollution at zero abatement costs, so that $MC(0)=0$ for all firms and there are no differences in the intercept of the marginal cost function. Second, it is these slopes that enter Equation (8), so they contain the relevant economic information.

A general way to model this is to suppose that all marginal cost curves can be written

$MC_i(A_i)=MC(A/\alpha_i)$, so the inverse marginal cost curves can be written $A_i(t) = \alpha_i A(t)$. Without loss of generality, we arbitrarily choose the reference curve $A(t)$ so that $\sum_i \alpha_i=1$. This structure subsumes a number of special cases. For example, it is consistent with simple linear marginal cost curves with slopes equal to α_i. More interestingly for our purposes, it is also consistent with convex marginal cost curves in *percentage* abatement. That is, suppose each state has the same shaped marginal cost curve, only re-scaled on the domain $[0, \bar{A}_i]$, where $\bar{A}_i$ represents maximal or 100% abatement in state i. In that case, $\alpha_i=\bar{A}_i/\sum_j \bar{A}_j$, the (renormalized) baseline emissions level.[5] As we shall see, this is a reasonable approximation to the empirically observed marginal cost curves. If Illinois and Maine release 200,000 tons and 5000 tons of SO_2 respectively when uncontrolled, it is simply easier for Illinois to abate 5000 tons than for Maine to do so. Accordingly, we shall assume for the remainder of this section that the weights α_i are baseline emissions.

In this case the first-order condition (7) now becomes:

$$\frac{dA}{dt}\sum_{i=1}^{N}\left(MNB_i - t_u\right)\alpha_i = 0. \tag{9}$$

Dividing through by dA/dt, re-arranging, and using $\sum\alpha_i=1$ gives

$$t_u^* = \sum_{i=1}^{N}\alpha_i MNB_i. \tag{10}$$

Again, the second-best uniform Pigouvian tax is a weighted average of each state's first-best Pigouvian tax levels. The weights are baseline emissions.

At first glance, it may appear that this result says nothing more than that large polluters carry more weight. However, this is only because high-polluting states (with high $\bar{A}_i$) have more elastic marginal cost curves. Low-polluting states have inelastic marginal cost curves, so they can be virtually ignored when computing the second-best uniform policy. If these slopes were the same, large baseline emissions per se would not affect marginal conditions and so would

[5] That is, if $A(t)$ represents the *percentage* abatement induced in any jurisdiction by t, then $A_i = \bar{A}_i * A$. We then simply renormalize A by multiplying by the constant $\sum_j \bar{A}_j$ so that $A_i = (\bar{A}_i/\sum_j \bar{A}_j)*A$.

have no effect on the optimal price.

This intuition is clear from the formula for deadweight loss relative to the first-best. The over-all deadweight loss of the uniform policy, relative to the first best, is approximately

$$DWL_u \approx \sum_{i=1}^{N} \frac{1}{2}(MNB_i - t_u^*)^2 \alpha_i \frac{dA}{dt}. \tag{11}$$

Substituting in the above expression for t_u^* and re-arranging slightly gives

$$DWL_u \approx \frac{1}{2}\frac{dA}{dt}\sum_{i=1}^{N} \alpha_i \left(MNB_i - \sum_{j=1}^{N} \alpha_j MNB_j \right)^2 = \frac{1}{2}\frac{dA}{dt}\hat{\sigma}_w^2, \tag{12}$$

where $\hat{\sigma}_w^2$ is the weighted empirical variance of the *MNB*. Thus, the welfare loss of the second-best uniform policy is proportionate to the weighted variance in marginal benefits across local jurisdictions. If there is no heterogeneity in benefits, then this policy is equivalent to the first best.

The importance of such heterogeneity generally is well-established in the environmental federalism literature (Oates 1972, 2002a, Dalmazzone 2006). However, to this point, the literature does not seem to have appreciated the importance of how heterogeneity in benefits interacts with heterogeneity in costs. In particular, note that the loss in welfare from the uniform policy is proportionate to the *weighted* variance in marginal benefits, where the weights are the cost scalings. For any fixed wedge between MNB_i and t_u^*, the decrease in welfare from the first best is scaled in Equation (11) by $\alpha_i \frac{dA}{dt}$, the slope of the marginal cost curve. Thus, if the marginal cost curve is highly inelastic, the distortion will be small.[6] This is precisely what happens for low values of $\bar{A}_i$.

Figure 1a and 1b illustrate this logic. The first panel shows a case where *N=2* and the marginal cost curves are identical for the two states, but $MNB_2 > MNB_1$. In this case, the uniform

[6] The logic is analogous to the Ramsey analysis of the deadweight loss of taxation or, more generally, Baumol and Bradford's (1970) analysis of optimal departures from marginal cost pricing subject to a constraint. Here, the constraint is the requirement of uniformity and the wedge is the difference between t_u^* and MNB_i.

policy proceeds by setting t_u^* equal to the simple average of the two *MNB* levels, equating the marginal deadweight loss in each state. (Although the totals are different, the derivative of deadweights losses A and B with respect to *t* are identical). The second panel is the same except that $\bar{A}_1 < \bar{A}_2$: State 1 has low baseline emissions and so its marginal cost curve becomes inelastic at lower levels of abatement. If t_u^* were set at the same level as before, the marginal deadweight loss around State 1 would be much lower than around State 2 because of the relative elasticities of the marginal cost curves. Total deadweight loss could be reduced by raising t_u^* closer to MNB_2. For example, the shaded areas in Figure 1b show the respective welfare gain in State 2 and loss in State 1 of increasing the pollution price to $t_u^*{}'$, which is a net gain in welfare. Although for the case of N>2 it will not be possible to equate the marginal deadweight loss in all states, the intuition for the role of marginal abatement costs still holds.

2.4. Comparison of Policies

This analysis has a very important implication for environmental policy in a federation: ceteris paribus, the more marginal abatement costs are convex (concave), the higher (lower) the level of welfare under a centralized policy relative to the devolved policies.[7] More precisely, suppose benefits MNB_i, spillovers (MNB_i - MB_{ii}), and cost scaling α_i are random variables and consider the following three assumptions:

Assumptions

1. Marginal social benefits, spillovers, and marginal cost scalings are uncorrelated: $MNB_i \perp \alpha_i$, $(MNB_i - MB_{ii}) \perp \alpha_i$ and $(MNB_i - MB_{ii}) \perp MNB_i$.
2. The distribution of marginal social benefits is symmetric, so that the third central moments can be ignored: $E(MNB_i - \overline{MNB})^3 = 0$.
3. Marginal abatement costs are increasing and third and higher orders can be ignored: $\frac{dA}{dt} > 0$, $\frac{d^3A}{dt^3} \approx 0$. Convexity is given by the second order: $\frac{d^2A}{dt^2}$ >/< 0.

Under these conditions, the following federalism propositions hold.

[7] We emphasize that we are speaking of *marginal* cost functions. With nonincreasing returns to scale, neoclassical cost functions are always convex, so marginal cost functions are necessarily non-decreasing. The convexity/concavity of such marginal cost functions is an empirical matter.

Proposition 1. *Ceteris paribus, as spillovers become less important, decentralized policies yield higher welfare. Moreover, as spillovers go to zero,* $\sum_{i=1}^{N}(MNB_i - MB_{ii})^2 \rightarrow 0$*, decentralized policies approach the first best.*

Proposition 2. *Ceteris paribus, as heterogeneity in abatement benefits become less important, the centralized policy yields higher welfare. Moreover, as heterogeneity goes to zero,* $\sum_{i=1}^{N}(MNB_i - \overline{MNB})^2 \rightarrow 0$*, the uniform policy approaches the first best.*

Proposition 3. *Ceteris paribus, as marginal abatement costs become more convex (concave), the centralized policy yields a higher (lower) level of welfare relative to local policies.*

Proof: *See the appendix.*

The first two propositions reflect the standard factors from the literature (e.g. Oates 1972, 2002a). We include them here only for completeness and to show that our model remains consistent with the standard intuition. The third proposition is new. Whereas the first two relate to the errors in the price signals implicit in the policies adopted by each level of government, the third relates to how these price signals translate into distortions in abatement. Although the proof involves some arithmetic, the intuition behind this proposition is straightforward. The centralized policy induces errors around the optimal value, being sometimes too high and sometimes too low. The state policies are always too low. But with convex marginal costs, the errors in the state policies, being always downward, systematically occur where the abatement supply curve is more elastic, leading to greater deadweight losses. With concave marginal costs, the opposite would be true.

The intuition can be seen again in Figure 1a. Again, there are two jurisdictions with identical marginal cost curves but with the heterogeneity in benefits as shown. Suppose further that spillovers are the same for each jurisdiction and equal to (MNB_2-t_u^*): thus, MB_2=t_u^* and MB_1=0. The central government of course chooses t_u^* with deadweight loss A+B, as before. The local jurisdictions choose t_2=MB_2 and t_1=0, respectively, with deadweight loss A+C. In all four cases (2 policies, 2 jurisdictions), the prices are off by the same amount in absolute value. But because the local jurisdictions systematically under-price pollution, whereas the central government is right "on average," elasticities are higher in the neighborhood of the local policies, and hence so is deadweight loss. Although the price effects are the same, the convex marginal cost curves insure that the Harberger triangles A, B, C are successively bigger.[8]

This example suggests another, somewhat stronger way to re-state the ceteris paribus condition in Proposition 3. Namely, if the first two factors, spillovers and heterogeneity, exactly offset, so that welfare under the centralized and devolved policies are identical with linear marginal cost curves, then welfare will be higher under the centralized policy when marginal costs are convex and higher under the devolved policies when they are concave. We state this formally in the following corollary.

Corollary to Proposition 3. *Suppose the problems of inter-jurisdictional heterogeneity in marginal benefits and inter-jurisdictional spillovers are equally balanced, so that*

$$\sum_{i=1}^{N}(MNB_i - MB_{ii})^2 \ = \ \sum_{i=1}^{N}(MNB_i - \overline{MNB})^2,$$

noting that $t_u^* = \overline{MNB}$. *Then social welfare under the centralized policy is greater than, equal to, or less than welfare under the devolved policies according to whether the marginal abatement cost curves are respectively convex, linear, or concave.*

Proof: *See the appendix.*

We conclude by noting that if marginal abatement costs and marginal benefits are negatively correlated (α_i and MNB_i are positively correlated), then relative welfare will be even higher under the centralized policy. In this case, t_u^* will be weighted upward toward the high-*MNB* states. If marginal costs are convex, so that $MC''(A)>0$, then at these higher pollution

[8] It is worth noting here a deceptively attractive non-theorem that has proven quite tempting both to us and to more than one commentator. In particular, reasoning analogously from Weitzman (1974), it would seem that if governments are using a uniform ambient quality standard, imposing uniform quantities of pollution across jurisdictions instead of uniform prices, then local jurisdictions would outperform the central policy if marginal costs are convex. In fact, this is not necessarily so. Figure 1A provides a counter-example. In this case, where there is no heterogeneity in costs, the central policy is the same whether framed as equating marginal costs or equating quantities. There is a one-to-one correspondence between the two. The central government would simply set the quantity in each jurisdiction associated with t_u again, outperforming the local policies as discussed previously. With heterogeneity in costs, this will not be so in general, but the counter-example disproves the non-theorem. The problem is that reasoning analogously from Weitzman's earlier work is misleading in this context. Whereas Weitzman's results provide insights into the relative performance of price versus quantity instruments based on the slope of marginal cost curves, our results provide insights into the relative performance of heterogeneous under-pricing versus homogenous average pricing, using *either* quantity *or* price instruments, based on the convexity of marginal cost curves. Further complicating the analysis of ambient standards is the fact that in practice they generally dictate a lower bound, giving an inequality rather than equality constraint (Oates, Portney, and McGartland 1989).

prices the other marginal cost curves will be especially inelastic. As we shall see, this insight is quite important for the case of air pollution in the US. As an empirical matter, large baseline polluters (high α states) like North Carolina and Illinois have high marginal benefits and small baseline polluters (low α states) like Maine and New Mexico have low marginal benefits.

3. Electricity and Pollution Models

We illustrate the importance of all three factors for one of the most important policy examples for environmental federalism: inter-state air pollution in the United States. Not only are the stakes of air pollution policies large, with estimated annual benefits from the Clean Air Act of $110 billion and annual direct compliance costs of $27 billion (US EPA 1999), but historically the level of government controlling standards, prices, and enforcement has been a matter of debate. Moreover, the lessons learned from this example have natural applications in other contexts as well, such as the European Union.

Our empirical methodology for comparing the trade-offs between local heterogeneity in damages versus inter-jurisdictional spillovers follows the approach taken by Banzhaf, Burtraw, and Palmer (2004), who studied a second-best uniform standard for the US electricity sector. Their work has also been used by Parry (2004, 2005) to help calibrate general equilibrium models of pollution control. The basic procedure involves two steps. First, a detailed model of the electricity sector simulates state-specific marginal abatement cost functions. Second, an integrated assessment model estimates the within-state and nationwide benefits of each state's abatement. The following two sub-sections discuss these two models in more detail, and a third discusses how we combine them to estimate the federalism trade-offs for air pollution.

3.1 Marginal Abatement Cost Functions

Our estimates of state-specific marginal abatement cost functions are based on output from the "Haiku" model of the electricity sector, developed at Resources for the Future (Paul and Burtraw 2002). It has been used in a number of peer-reviewed articles (e.g. Banzhaf et al. 2004, Burtraw et al. 2010, Palmer and Burtraw 2005, Pizer et al. 2006). In essence, it is a simulation model of regional electricity markets along with interregional electricity trade in the United States.

The electricity model computes market equilibria in 13 regions corresponding to the National Electricity Reliability Council (NERC) subregions, for three seasons (winter, summer, and spring/fall), and for four time blocks (base load, shoulder, peak, and super-peak), for a total of 156 markets. The demand side of the market is the aggregate of three sectoral electricity demand functions (commercial, industrial, and residential). Demands for electricity have a constant elasticity calibrated from the academic literature.

The model assigns all individual power plants in the continental U.S. to one of 46 model plant types. The model plants differ by six fields: plant technology, fuel type, coal demand region, pollution scrubbers, relative efficiency, and existence status. Individual plants also remain differentiated by capacity and age. The model accounts for developments in wind, solar, and hydroelectric power. Electricity supply is also a function of endogenous fuel prices for each fuel type. Fuels include 14 coal types, natural gas, and biomass, and delivery prices of each include a region-specific transportation cost. Finally, the model can also accommodate Pigouvian taxes on pollution or pollution caps.

Using these supply and demand inputs, the model solves for electricity quantities, prices, and pollution outputs. Recognizing that power plants are long-term investments, the model solves for a 20-year time horizon, discounting future revenues and costs back to the decision-making point. In doing so, it solves for every fifth year and interpolates the results to intermediate years. It also accounts for the competitive and regulated price regimes operating in each region.

The model's data mainly comes from the Energy Information Administration (EIA) and the Federal Energy Regulatory Committee (FERC), with some additional information from the Environmental Protection Agency (EPA). For additional details on the model, see Paul and Burtraw (2002).

3.2. Abatement Benefit Functions

We use the Tracking and Analysis Framework (TAF) integrated assessment model to estimate the benefits of pollution abatement. Integrated assessment models make extensive use of transfer methods, which transfer information from the context of previous research to a new policy context (Desvousges et al. 1998, Navrud and Ready 2007). Integrated assessment models of air pollution bring together contributions from many different areas of science, including meteorology and atmospheric chemistry, toxicology and epidemiology, and economics. All of the information works together allowing one model to compute all of the relevant effects together.

Several integrated assessment models of air pollution have been developed in recent years. Desvousges et al. (1998) construct a model to study externalities from new power plant locations in Minnesota. Muller and Mendelsohn (2007, 2009) use the Air Pollution Emissions Experiments and Policy analysis model (APEEP) to examine the marginal damages of releasing one additional ton of emissions from any of 10,000 sources in the US. Rowe, Lang, and Chestnut (1996) use the computerized Externality Model (EXMOD) to measure externalities from electricity production in New York. The US EPA uses a model called BENMAP (Abt 2008).

TAF consists of several modules, each of which was developed by a team of experts in their respective field.[9] The first module is a set of seasonal source-receptor matrices, which track pollutants from their source to the locations that they damage. The source-receptor matrices in TAF are simplified versions of the Advanced Source Trajectory Regional Air Pollution model (ASTRAP), which is based on 11 years of weather data. TAF identifies a source centroid and a receptor centroid for each state based on electricity generation patterns and population respectively. These centroids are used to compute reduced form source-receptor matrices of state-to-state pollution flows. The pollution flows account not only for a simple Gaussian dispersion of gasses, but also for the down-stream chemical reactions which convert SO_2 and NO_x to sulfates and other fine particulates.

The second module uses epidemiological relationships to estimate the effect of pollution concentrations in each state on mortality rates and incidences of various short-term and chronic illnesses.[10] These estimates are based on total populations and their age-distributions within each state. Mortality rates are the most important driver of damages, and are based on a cross-sectional study by Pope et al. (1995). The morbidity effects include, for particulates, chronic bronchitis, chronic cough, acute bronchitis cases, upper respiratory symptoms, cough episodes,

[9] See Lumina (2009) and Argonne National Labs (1996) for overviews of the basic architecture of the model. Our version of the model updates several functional relationships from the earlier versions described there. The updates, noted in more detail below, include alternative estimates of mortality effects and estimates of the valuation of all health effects.

[10] In principle, the model might also account for effects on agriculture, materials, and visibility. However, previous work has found that health effects account for the vast majority of damages (Desvousges et al. 1998, Muller and Mendelsohn 2007, Rowe et al. 1996).

and croup; for SO_2, they include chest discomfort and cough episodes; and for NO_2, they include eye irritation and upper respiratory symptoms.

The third and final module assigns monetary values to these damages based on economic studies of the value of statistical life and other health valuation studies. Most importantly, the value of a statistical life in TAF is taken from a meta-analysis by Mrozek and Taylor (2002) and is $2.32 million (in 2000 dollars). This value is on the low end of the range in the literature, and compares to the value of $5.5 million (in 2000 dollars) used by the EPA in its benefit-cost analyses. Values for short-term morbidity effects are taken from a meta-analysis by Johnson et al. (1997).

TAF takes a baseline emissions scenario and a policy emissions scenario and calculates the total damages of each by state. The difference is the effect of the policy.

3.3. Policy Simulations

We use these models to identify a fully differentiated policy, a second-best federal uniform policy, and individual states' self-regarding policies in the following way. We compute these policies for 45 of the 48 continental states.[11]

In the first step, successive levels of SO_2 or NO_x taxes are input into the electricity model, which then estimates the corresponding level of pollution abatement in each state for that tax level (Banzhaf et al. 2004). The scenarios include a simulated baseline of no control, in which abatement investments such as scrubbers, which are found on power plants today as a result of current regulations, are removed. From this simulated counterfactual, SO_2 taxes are added, varying from $500 to $6500 per ton. The NO_x taxes vary from $700 to $1500. This procedure traces out a series of state-specific marginal abatement cost functions (or abatement supply functions) that form one primitive for our analysis of environmental federalism. Adjustments allowed in the model include fuel switching, investment in post-combustion controls such as scrubbers, investment in new gas or renewable energy, and conservation by end-users induced by

[11] The District of Columbia, Rhode Island, Vermont, and Idaho are excluded from the analysis as they do not contribute any significant level of emissions. However, when computing national benefits, we do account for benefits accruing to these states from emissions reductions in the other 45 states.

higher electricity prices.[12]

We emphasize that there is nothing about this procedure that limits its applicability to only Pigouvian tax policies. Inputting various pollution taxes into the model is simply a heuristic for tracing out marginal abatement costs. The resulting abatement cost curves can be used to analyze any policies, including the cap-and-trade policies that have dominated US air pollution policy since 1990.

In constructing a specific state's abatement cost function, we allow for inter-state trading in electricity, but assume that the state adopts policies to limit the "pollution haven effect," or the "leakage" of pollution to other states.[13] Doing so may well be consistent with the state's self-interest, as otherwise leakage from a state to its neighbors would spill back over into the state. More to the point, empirically, individual states that are adopting policies separate from federal requirements are in fact addressing such leakage. California, which has mandated carbon reductions by 2020, is requiring that load-serving entities incorporate a shadow price on electricity imports to account for the pollution content of those imports. Although no tax is ever levied, load-serving entities must act *as if* there were such a tax in their decision-making. California also is requiring that any long-term purchases of power be subject to a cap on emissions per megawatt of electricity. In addition, northeastern states in the Regional Greenhouse Gas Initiative (RGGI) are considering similar policies, as well as including the pollution-content of electricity imports as part of a total pollution cap (Farnsworth et al. 2007). We model the first of these policies, adopted in California, in which dispatch within a state proceeds "as-if" there were a tariff on the pollution content of imports, with the hypothetical tariff equal to the state's marginal abatement costs. (Equivalently, the state sets an overall cap on pollution, with the pollution content of imports counting toward the cap.)

The information that is observed from the electricity model is a sequence of price-pollution pairs. Figure 2 shows examples of the marginal abatement cost functions for SO_2 for four states: Colorado, New York, Texas, and Connecticut. The origin is the simulated baseline of no control, and involves much lower investment in abatement technologies (and much more

[12] See Banzhaf et al. (2004) for a detailed breakdown of these equilibrium adjustments at different tax levels, under a simulation similar to the uniform policy considered here.

[13] On the treatment of such leakage in US regional policies, see Burtraw et al. (2006), Farnsworth et al. (2007), and Sue Wing and Kolodziej (2009).

pollution) than found under actual regulatory environments today. The dotted line is a simple linear interpolation of the output from the electricity model. The solid line imposes some smoothness on the raw data as well as monotonicity, using non-parametric local regression.[14] We impose some smoothness on the data because the raw data for some small states like Connecticut, shown in Figure 2d, exhibit decreasing marginal abatement costs over some intervals. These are due to simulation error in the model, as well as the effects of inter-state trade.[15] The case of Connecticut is particularly extreme in this regard, because of its low emissions. There, a little noise in the data can appear significant in percentage terms. In most cases, such reversals are very small (e.g. New York and Texas shown in Figures 2b and 2c) or non-existent (e.g. Colorado shown in Figure 2a). (Note how the scale of the *x*-axis is two orders of magnitude smaller in Connecticut than New York or Texas.)

Importantly, the graphs reveal that marginal costs are far from linear. Instead, they are very elastic at low levels of abatement and very inelastic--indeed, practically vertical--at high levels of abatement. This is an important finding. As noted in Section 2, it implies that states with low baseline emissions will have more inelastic costs around average benefits, giving them low weight in the calculation of t_u^*. Because their abatement benefits tend to be lower, this raises t_u^*.

On the benefits side, we input the emissions from each state separately into the TAF model. By varying one state's emissions and leaving all other states at their baseline emission levels, we thus generate state-specific marginal benefit functions. For each state's emissions, we construct two such benefit functions, one counting only the within-state benefits, the other counting all national benefits. Because the epidemiological literature suggests that health effects are virtually linear across the relevant range of pollution concentrations, marginal benefits for each state are necessarily constant, a standard result in air pollution policy analysis.

[14] In particular, we use a locally weighted scatterplot smoothing (Lowess) model (Fan and Gijbels 1996). This is a variant of local polynomial kernel regression, but it downweights large residuals and uses a variable bandwidth parameter determined by the distance from each point to its nearest neighbors. We use a tricubic kernel.

[15] Even with "as if" pollution taxes at the border, substitution between out-of-state and within-state generation may well occur over some ranges of pollution taxes if abatement costs differ. Although such effects our entirely plausible in general equilibrium, we impose monotonicity and smoothness on the data to facilitate partial equilibrium analyses.

Figure 3 puts the cost and benefit sides of the model together for four states: Louisiana, California, Florida, and Illinois. The solid upward sloping line is the estimated marginal cost of abatement curve. The three dashed lines represent three prices. All the figures plot $3912, which as we discuss below is our estimate of t_u^*. The lower of the other two is the benefits for a state of reducing its own pollution; the upper of the other two is the benefits to the entire nation. The figure illustrates some of the differences across states. In most states, within-state pollution costs are small and there is a large gap from the national costs. In a large state like California, a larger share of the marginal damages from emissions falls within the state, and even MB_{ii} is greater than the average national benefit.

We use these data to consider three policies as described in Section 2. First, we consider a reference policy that accounts for both inter-jurisdictional spillovers and heterogeneity in damages. In the reference policy, each state's marginal abatement costs are equated to its marginal national benefits. That is, in each state, we find the intersection of the marginal cost curve with the upper dashed lines depicted in Figure 3. If marginal benefits of abatement were uniform within states, this policy would be the first best.[16]

To this reference policy, we compare the two second-best policies which represent the tradeoffs inherent in environmental federalism. One such second-best policy is one in which air pollution policies are devolved to each state. This policy has the advantage of allowing for heterogeneity across states, but the disadvantage that self-interested states will ignore inter-jurisdictional spillovers. To find the outcomes of this policy, we equate each state's marginal cost curve with MB_{ii}.

Finally, following Banzhaf et al. (2004), we consider a second-best policy in which the Federal government sets a single Pigouvian tax (or single pollution cap with one-to-one inter-state trading ratios). This is the policy regime that prevails in the United States today. This requires aggregating the marginal cost curves to a national marginal cost of abatement curve. It similarly requires aggregating marginal benefits. Marginal benefits are no longer constant, as at each point the marginal unit of pollution is associated with a different location, with differing

[16] Muller and Mendelsohn (2009) show that within-state heterogeneity in benefits can be substantial. However, since our goal here is to compare the effect of policy decisions at local versus national jurisdictions, this reference policy is the appropriate standard of comparison, not a fully plant-level-differentiated first best.

damages. However, there is no consistent trend in benefits, so smoothing this benefits curve results in a roughly flat marginal benefit function.

By aggregating the benefits and costs accruing to each state under each scenario, we can now compare the net benefits for each policy.

4. Results

To facilitate in-depth discussion, we concentrate on the results from SO_2 policies; NO_x policies are summarized briefly afterwards. Tables 1 and 2 provide detailed information about the simulations from the three SO_2 policies. Table 1 provides the contribution to national welfare from the abatement activities of each state, for each policy, relative to a simulated baseline of no pollution controls. These net benefits are computed by multiplying abatement by the (constant) national marginal benefits, and subtracting the area under the abating state's marginal cost curve. Column 1 shows a state's contribution to national benefits under the reference policy. Column 2 shows the national net benefits achieved when a state acts in its own interests. And Column 3 shows a state's contribution when it complies with a national uniform policy.

The bottom line of Table 1 is literally the bottom line of the empirical application. It shows the total benefits of each policy, and the difference from the first best. It shows that the benefits of the fully differentiated first-best policy are $59.7 billion, consistent with other estimates of substantial gains from national pollution control (Banzhaf et al. 2004, Muller and Mendelsohn 2007, US EPA 1999). More to the point, the states on their own are estimated to achieve national net benefits of $40.9 billion, simply acting out of their own self-interest. This is a loss of 31.5% percent of the total potential benefits, which is substantial, but perhaps smaller than one might have guessed. More surprising is that the second-best uniform policy achieves benefits of $59.6 billion, a loss of only 0.2% of the first-best benefits![17]

[17] Our estimated gain of differentiation of just over $100m compares to a recent estimate by Muller and Mendelsohn (2009) of $300m to $900m. These are of the same order of magnitude (and all under 2% of first-best benefits), but the differences warrant discussion. As noted above, they stem from the different policy contexts. Muller and Mendelsohn consider differentiation around *status quo* aggregate emissions, whereas we consider the second-best uniform policy, with much higher levels of abatement. Given the convexity of the cost curves, the deadweight losses around these points from imposing uniformity will be different. There are other differences as well. Our model has a more detailed treatment of plant-specific abatement costs, but their model has a more detailed treatment of plant-specific benefits. That is, "heterogeneity" means something different in the two applications: necessarily, the gains from considering inter-plant heterogeneity will be larger than considering inter-jurisdictional heterogeneity.

To understand these results, Table 2 provides the estimated optimal marginal abatement costs of each policy for each state as well as the associated level of abatement for that marginal abatement cost. We will refer to this table in the following three sub-sections, which consider the results from each of the three policies in more detail.

4.1. Reference Policy

Column A of Table 2 shows the marginal national benefits of abatement in each state, which corresponds to the Pigouvian tax on SO_2 emissions in the reference policy (or price for a pollution permit in that state). For comparison, prices for SO_2 permits have ranged from $100 to $1600 in recent years. From these data alone, we can see that there is substantial inter-state heterogeneity in the marginal benefits of abatement, a factor favoring local policies, as described in Proposition 2. Marginal benefits are lowest in Maine, at $1091/ton SO_2, but 5.7 times higher in California, which has the highest marginal benefits at $6199/ton SO_2. The median is $3181. These differences are not due only to outliers. The average of the marginal benefits among the ten highest-benefit states is $4703/ton, whereas the average among the ten lowest-benefit states is $1398/ton—still a 3.4-fold difference.

Naturally, there is substantial heterogeneity in optimal abatement as well, shown in Column B, ranging from 925 tons in Montana to 2.1 million tons in Illinois. Not only that, there is substantial heterogeneity in relative abatement, ranging from under 10% in North Dakota and Montana to 98.5% in Illinois, relative to a simulated baseline of no taxes or caps. The mean is 72.1% abatement.[18]

From these data, it would appear that there would be substantial welfare gains from accounting for such heterogeneity in pollution policies. As we shall see, however, this is not so because of the role of marginal costs.

4.2. State Policies

The next three columns of Table 2 consider the policy of devolving all control of SO_2 to the states. In this policy, individual states are free to set their own price of pollution, but in doing so we assume they consider only their own benefits and ignore inter-state externalities.

Column C shows the within-state marginal benefits, which are the Pigouvian taxes (or in-

[18] Data on percentage abatement are not shown in the table, but are available upon request.

duced marginal abatement cost) that self-interested states would adopt on their own. Column D shows those benefits relative to total national benefits (i.e., the percentage of marginal benefits internalized within-state). On average, only 16% of marginal benefits are internalized within-state and prices are on average $2592 too low. Concordant with Proposition 1, state policies that fail to internalize the other 84% of benefits are bound to be sub-optimal. Figure 4 plots (in solid diamonds) the pollution prices that each state would choose for itself against the optimal prices (i.e. Column C against Column B). Each point is below the 45-degree line because states are ignoring inter-state spillovers.

However, there is also substantial geographic heterogeneity. California is again the state with the highest within-state benefits, at $4975/ton SO_2, while North Dakota has the lowest at only $19/ton, a difference of 257-fold. Even averaging the top-10 and bottom-10 states, the difference is $1569/ton vs. $70/ton, a factor of 22.4. This heterogeneity in MB_{ii} reflects the underlying heterogeneity in marginal national benefits (MNB_i) that were displayed in Column A. The correlation between the two is 0.59, indicating that the *pattern* of the first-best values are reflected in states' own incentives. The correlation is not perfect because of variation in the extent to which national benefits are internalized within-state (i.e. the ratios MB_{ii}/MNB_i). California again leads the way here, with its within-state benefits capturing 80.3% of the national benefits (Column D). In the case of California, the size of the state suggests that much of the exposure from emissions will be within the state, while downwind states like Nevada are sparsely populated. The other top-10 states in terms of internalizing most of their damages are all Atlantic seaboard states (or, in the case of Pennsylvania, close to the coast), because much of their downwind spillovers falls relatively harmlessly over the ocean. On average, these ten states have within-state marginal benefits that are 38.4% of the national benefits. At the opposite extreme, the ten states least likely to internalize their national damages are all sparsely populated states, mostly in the West and Midwest—states like Wyoming and the Dakotas. On average, these ten states have within-state marginal benefits that are only 3.3% of national benefits. These patterns can go a long way toward explaining which states we observe to be adopting policies beyond federal requirements, states like California, Texas, North Carolina, and northeastern states (Chupp 2009).

Finally, Column E shows the abatement under the simulated state policies and Column F shows this abatement relative to the reference policy level. Figure 5 plots each state's self-chosen abatement against their abatement in the reference policy (again in solid diamonds). Whereas the average state chooses a price that is only 16.3% of total benefits, it does achieve 36.5% of optimal abatement. Moreover, total abatement is 57.8% of the optimal amount (because on average the large polluters internalize more than the small polluters). This indicates that the marginal abatement cost elasticities are generally low over the relevant range. Indeed, some states come quite close to the optimum: California for example achieves 99.9% of the omtimal abatement just by behaving in its own interest, and New Jersey, North Carolina, Maryland and Virginia all achieve over 80%. On the other hand, Kansas, North and South Dakota, and Wyoming all abate less than 2% of the optimal quantity of abatement.

4.3. Uniform Policy

Last, we consider the second-best federal policy, which restricts marginal abatement costs to be equal in all states. Figure 6 shows the solution for SO_2, in which we calculate the optimal uniform pollution price to be \$3912. Again, this compares to an average SO_2 price in the US of \$100 to \$1600 prevailing in recent years. This type of policy is the one studied by Banzhaf et al. (2004), and our results are close to theirs.[19] However, they did not consider the relative efficiency of this policy to first-best or the issue of inter-state heterogeneity in damages, which is the focus of this paper.

The model in Section 2 suggests that if all marginal abatement cost curves have the form $MC_i(A_i)=MC(\alpha_i A)$, then the uniform price would be a weighted average of the states' damages, with the α's as weights. Further, we argued that if all marginal abatement cost curves had the same shape over the domain $[0, \bar{A}_i]$, where $\bar{A}_i$ is 100% abatement in state i, then the $\bar{A}_i$ could serve as weights. Using simulated baseline emissions as weights in this way, we compute a weighted average pollution price of \$3953—quite close to our estimated optimal t_u of \$3912. Thus, as discussed in Section 2, supply elasticities play a crucial role in determining the uniform price.

[19] Our second-best uniform SO_2 price of \$3912 compares to their estimate of \$3500. The difference is due to an inconsistency embedded in their results that we have eliminated. In particular, in their model ancillary benefits of NO_x reductions from SO_2 "taxes" (or vice versa) were included in the net benefit function, but general equilibrium shifts in abatement cost curves were ignored. We use a partial equilibrium approach that looks only at one pollutant at a time. This approach is more straight-forward and more consistent. Sensitivity analyses using their estimates suggest this would not qualitatively affect the results found here.

Column G of Table 2 shows how this price compares to national benefits from abatement in each state. These data are also plotted in Figure 4 (open squares). Obviously, by definition, this policy ignores all heterogeneity in marginal benefits. Accordingly, it systematically provides too little incentive for abatement in high-benefit states and too much incentive in low-benefit states. In California, for example, this value of \$3912/ton SO_2 is only 63.1% of the first-best value. The average across the ten state with the highest abatement benefits is 84.2% of the first-best value. At the same time, the uniform policy induces substantial over-control in low-benefit states. The uniform SO_2 price is 358.5% higher than the abatement benefits in Maine, the lowest-benefit state. The average across the ten lowest benefit states is 287.5% of the first-best values. Because of this over-control, eight Western states plus West Virginia and Alabama actually experience greater welfare gains under the policy in which all states internalize only within-state benefits than under the uniform policy. However, because they enjoy the control of upwind polluters, the other 35 states in our analysis do better under the uniform policy.[20]

It is informative to compare the uniform price with the states' policies. As noted above, on average states' self-chosen prices are \$2592 too low; the average of percentages is 84% too low. By comparison, the average of the *absolute value* of the error in the uniform price is \$1092; the average of absolute percentage differences is 40%. These errors are about half that made under the state policies. Consequently, for the case of SO_2 pollution in the US, we can conclude that on balance the problem of ignoring inter-jurisdictional spillovers outweighs the problem of ignoring heterogeneity in marginal benefits. Based on the factors described in Propositions 1 and 2, we would conclude that the national policy is better than the state policies.

However, the errors made by the uniform policy are still significant, so it is surprising that the net benefits of this policy are as much as 99.8 percent of the benefits under the reference policy. The explanation lies in our Proposition 3, which relates the quantity responses to the policy to the convexity of the marginal cost curves. Column H of Table 2 displays the abatement in each state induced by the uniform price, and Column I displays this amount relative to the reference policy. Figure 5 graphs the relationship (Column H versus Column B). As seen in the figure, most states are on or very close to the 45-degree line under the uniform policy, indicating

[20] In computing these distributional welfare effects, we assume any revenues from taxes or permit auctions are returned to the states lump-sum.

abatement near first-best levels.

Thus, the reason for the near-perfect performance of the uniform policy is not just that the errors in the price signals are smaller. It is also that they occur at higher prices on average, where the marginal abatement cost curves are more inelastic. As shown in Figure 3, our estimated marginal cost curves exhibit a good deal of convexity, and the uniform policy tends to occur in a region where they are quite inelastic. Accordingly, errors in price signals correspond to small errors in abatement, and hence small deadweight losses. This is the new relationship identified in Proposition 3. Figure 7 confirms this intuition. It plots the arc elasticity over the relevant range of the marginal cost curve for the uniform policy against the respective elasticity for the state policy.[21] The figure shows that the elasticities are lower than one for all but three of the states under the uniform policy and under 0.75 for half; many are near zero. The elasticities are still lower than one for about three-quarters of the states under the states' policies, but the elasticities there are higher than under the uniform policy for all but two states. To the best of our knowledge, the important role of marginal cost elasticities and the way they interact with heterogeneity in benefits has been missed in the environmental federalism literature.

4.4. Sensitivity Analysis

In the TAF model, heterogeneity in marginal benefits arises from differences in air dispersal and differences in downwind population densities and age distributions. These result in heterogeneity in the injuries resulting from emissions at different locations. However, the model imposes homogeneity in the willingness to pay for a specific effect. In particular the value of a statistical life (VSL) is assumed to be the same in all states. In fact, the VSL literature finds a clear relationship between income and willingness-to-pay (WTP) for health risk reduction. This relationship can be used to adjust the benefits derived from TAF to take account of inter-state differences in income. First, we take the calculated income elasticity from the VSL literature. Mrozek and Taylor (2002) and Viscusi and Aldy (2003) estimate a range of income elasticities varying from 0.37 to 0.85. We use this range of elasticities, together with inter-state differences in mean income, to compute state-specific VSLs.

Surprisingly, larger income elasticities actually cause the net benefits of the state policy

[21] That is, for the two second-best policies, it computes the elasticity as the percentage deviation from the first-best level of abatement divided by the percentage deviation from the first-best price.

to fall slightly while the uniform policy benefits rise slightly, further exacerbating the difference between the two policies.[22] This result is somewhat counterintuitive. As the income elasticity rises, so does state level heterogeneity in damages.[23] Since heterogeneity in damages is the rationale for the possible superiority of state-level policies, it would seem that a higher income elasticity should improve the position of the state policies relative to the uniform policy. However, the result is driven by the fact that lower-income states tend to be upwind of higher income states in general, so that spillovers become more important.

4.5. Nitrogen Oxides

In addition to considering the case of SO_2 pollution, we also consider nitrogen oxides (NO_x), the second-most important pre-cursor of urban air pollution in the US. We find similar results, which are if anything more pronounced. With NO_x the state policies result in a loss of 76.2% of the potential benefits, while the uniform policy results in a loss of 2.32%. The uniform policy again approximates the fully differentiated solution fairly well. These results are available upon request.

5. Conclusion.

Improvements in air pollution have been some of the most important environmental achievements in many nations over the last 50 years. Air pollution exhibits the classic tradeoff of environmental federalism. It can travel great distances, making it a transboundary problem. At the same time, its damages are quite heterogeneous, depending on downwind population density.

In the United States, initial control by the states has been ceded to the federal government over time, especially with the passage of the 1970 Clean Air Act. Our analysis suggests this centralization is consistent with welfare optimization, for two reasons. First, the standard theory suggests that centralization is appropriate when inter-jurisdictional spillovers are more important that heterogeneity in damages, and we find that this is indeed the case for air pollution in the US. Second, our theoretical model shows that in addition, centralization will be more appropriate when marginal costs are increasing in abatement, which we also find to be the case for US air pollution. As a consequence of these two factors, the state policies lose 31.5% of potential SO_2

[22] Results available upon request.

[23] The standard deviation of state level benefits is 801.44 when $\eta = 0$, but rises to 860.43 when $\eta = 0.75$.

benefits, whereas the central uniform policy loses only 0.2%. Results are similar for NO_x.

In undertaking this analysis, we might be accused of committing the nirvana fallacy. It is important to acknowledge that while we show that, hypothetically, a uniform policy in the US could achieve something close to the second-best, in fact the US federal government has not actually adopted anything like this policy, despite having 40 years since the passage of the first Clean Air Act to get it right. This failure opens the door to questions about government failures and the political economy of pollution control. Decentralization may allow better oversight by citizens, provide discipline if citizens "vote with their feet," and encourage experiments in the laboratories of democracy. These may be the best reasons to pursue decentralization (Anderson and Hill 1997, Oates 2002a).

But in another sense our results may have broader applicability. Indeed, they may be viewed as one more interpretation of the so-called "Precautionary Principle." This idea has played a leading role in environmental policy since at least 1992, when it served as a guiding principle for both the Maastricht Treaty and the Rio Earth Summit. Heretofore somewhat inchoate, the notion of the precautionary principle is roughly that, given uncertainty about optimal regulation, over-abatement is to be preferred to under-abatement. Our results suggest a new, rigorous sense in which this may be true. If marginal abatement costs are increasing at an increasing rate in abatement, over-pricing pollution by a given amount will result in a lower welfare loss than under-pricing it by the same amount. If the optimal policy is for some reason not available, resolving "ties" in favor of the policy with higher pollution prices will raise economic efficiency.

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Table 1—Net Benefits of SO_2 Control

Contribution from Abatement in…	Net Benefits from Reference Policy	Net Benefits from State Policy	Net Benefits from National Uniform Policy
AL	$661,028,298	$33,016,753	$661,028,298
AZ	$6,391,725	$1,722,498	$573,964
AR	$1,305,728,466	$706,103,362	$1,305,634,156
CA	$34,485,744	$34,483,447	$34,477,369
CO	$31,005,685	$9,010,639	$21,002,010
CT	$31,380,594	$24,492,181	$31,375,460
DE	$303,794,021	$48,338,057	$303,106,444
FL	$996,720,290	$803,722,133	$996,701,970
GA	$2,602,325,127	$1,597,896,943	$2,602,331,630
IL	$8,073,744,024	$6,921,572,918	$8,073,744,024
IN	$5,374,877,882	$3,966,470,718	$5,374,810,768
IA	$60,972,390	$5,604,278	$58,279,284
KS	$88,499,986	$1,779,092	$87,853,729
KY	$1,308,859,577	$312,105,142	$1,308,855,956
LA	$713,810,411	$541,137,044	$713,789,372
ME	$1,909,834	$1,187,025	$381,291
MD	$2,497,197,282	$2,191,571,450	$2,497,213,514
MA	$15,238,952	$12,215,991	$14,500,879
MI	$4,011,629,201	$3,496,625,444	$4,011,731,564
MN	$16,127,884	$2,017,672	$14,128,508
MS	$96,555,836	$4,083,957	$96,555,836
MO	$918,321,033	$94,300,466	$918,312,248
MT	$375,060	$33,443	-$4,057,525
NE	$8,876,294	$595,494	-$4,260,891
NV	$118,046,805	$9,431,228	$115,377,440
NH	$4,387,117	$317,921	$1,678,970
NJ	$365,267,429	$341,020,573	$364,535,077
NM	$877,975	$133,396	$547,414
NY	$628,597,109	$519,436,239	$628,568,301
NC	$7,545,447,495	$6,896,616,405	$7,532,570,699
ND	$531,592	$18,371	-$9,102,678
OH	$2,923,193,583	$1,780,222,678	$2,922,867,427
OK	$1,093,557,983	$434,499,547	$1,093,469,228
OR	$17,618,432	$2,314,769	$17,177,875
PA	$1,979,018,950	$1,370,518,302	$1,978,933,386
SC	$1,706,878,513	$1,432,739,626	$1,705,129,316
SD	$1,334,581	$53,668	-$1,264,515
TN	$947,151,775	$242,834,499	$947,139,955
TX	$2,293,320,237	$1,777,032,495	$2,292,121,469
UT	$4,648,263	$736,544	-$2,774,690
VA	$2,774,857,978	$2,508,986,398	$2,770,717,810
WA	$9,202,889	$3,471,904	-$4,757,596
WV	$5,462,105,096	$1,033,766,266	$5,462,272,608
WI	$2,695,094,557	$1,748,745,698	$2,694,695,095
WY	$4,894,636	$183,164	-$6,031,187
Totals	$59,735,888,591	$40,913,165,839	$59,621,941,265
Difference from Optimal NB		$18,822,722,751 (31.5%)	$113,947,326 (0.2%)

*Net benefits presented here are the nation-wide benefits of reduced emissions in the given state minus the state's costs of attaining that level of abatement.

Table 2—Marginal SO_2 Abatement Costs (or Pollution Price) and Associated Abatement Levels

	A	B	C	D	E	F	G	H	I
State	**Pigouvian Price (2000 $)**	**Pigouvian Abatement (Tons)**	**State-Policy Price (2000 $)**	**State Price as % of Pigouvian**	**State Level Abatement (Tons)**	**State Abatement as % of Pigouvian**	**$3912 Uniform Tax as % of Pigouvian**	**Uniform Price Abatement (Tons)**	**Uniform Abatement as % of Pigouvian**
AL	$4,133.10	283,160	$343.58	8.3%	8,335	2.9%	94.7%	283,160	100.0%
AZ	$1,707.51	7,466	$247.80	14.5%	1,088	14.6%	229.1%	14,004	187.6%
AR	$4,637.93	334,470	$375.59	8.1%	158,670	47.4%	84.3%	334,040	99.9%
CA	$6,199.27	7,156	$4,975.46	80.3%	7,127	99.7%	63.1%	7,149	99.9%
CO	$1,632.33	44,902	$291.53	17.9%	6,061	13.5%	239.7%	69,091	153.9%
CT	$3,739.77	11,353	$1,060.46	28.4%	7,225	63.6%	104.6%	11,415	100.5%
DE	$2,526.79	146,720	$81.56	3.2%	19,444	13.3%	154.8%	148,490	101.2%
FL	$3,528.00	389,960	$1,240.30	35.2%	257,900	66.1%	110.9%	390,020	100.0%
GA	$3,825.17	902,190	$482.79	12.6%	445,870	49.4%	102.3%	902,220	100.0%
IL	$4,428.95	2,107,100	$837.04	18.9%	1,664,600	79.0%	88.3%	41,494	119.6%
IN	$4,271.14	1,478,700	$435.29	10.2%	978,530	66.2%	91.6%	2,107,100	100.0%
IA	$3,184.11	34,705	$139.51	4.4%	1,800	5.2%	122.9%	1,478,600	100.0%
KS	$2,943.90	54,528	$113.87	3.9%	616	1.1%	132.9%	56,226	103.1%
KY	$4,362.10	403,580	$307.69	7.1%	74,165	18.4%	89.7%	403,800	100.0%
LA	$4,122.66	208,060	$657.81	16.0%	140,300	67.4%	94.9%	207,970	100.0%
ME	$1,091.30	2,605	$302.32	27.7%	1,263	48.5%	358.5%	4,094	157.1%
MD	$3,874.41	736,320	$654.99	16.9%	605,860	82.3%	101.0%	736,350	100.0%
MA	$2,304.91	10,954	$1,063.06	46.1%	6,568	60.0%	169.7%	12,223	111.6%
MI	$3,580.13	1,352,700	$534.50	14.9%	1,050,300	77.6%	109.3%	1,354,900	100.2%
MN	$2,973.92	12,275	$399.84	13.4%	727	5.9%	131.5%	16,239	132.3%
MS	$3,893.92	46,223	$293.67	7.5%	1,090	2.4%	100.5%	46,223	100.0%
MO	$3,682.91	376,200	$260.87	7.1%	26,545	7.1%	106.2%	376,480	100.1%
MT	$1,104.10	925	$52.39	4.7%	31	3.4%	354.3%	5,967	645.4%
NE	$1,584.08	10,996	$52.60	3.3%	382	3.5%	247.0%	22,663	206.1%
NV	$2,389.29	104,360	$126.13	5.3%	4,054	3.9%	163.7%	111,400	106.7%
NH	$1,474.36	7,488	$134.77	9.1%	226	3.0%	265.3%	12,872	171.9%
NJ	$4,922.04	94,464	$2,297.02	46.7%	81,956	86.8%	79.5%	93,173	98.6%

	A	B	C	D	E	F	G	H	I
State	**Pigouvian Price (2000 $)**	**Pigouvian Abatement (Tons)**	**State-Policy Price (2000 $)**	**State Price as % of Pigouvian**	**State Level Abatement (Tons)**	**State Abate-ment as % of Pigouvian**	**$3912 Uniform Tax as % of Pigouvian**	**Uniform Price Abatement (Tons)**	**Uniform Abatement as % of Pigouvian**
NM	$1,633.95	934	$99.16	6.1%	84	9.0%	239.4%	1,441	154.3%
NY	$3,889.20	205,350	$1,249.50	32.1%	149,600	72.9%	100.6%	205,610	100.1%
NC	$4,753.78	1,842,500	$1,071.42	22.5%	1,537,000	83.4%	82.3%	1,815,600	98.5%
ND	$1,109.55	958	$19.34	1.7%	17	1.7%	352.6%	7,767	810.5%
OH	$3,874.56	1,055,500	$549.61	14.2%	491,990	46.6%	101.0%	1,058,100	100.2%
OK	$3,455.63	412,000	$261.44	7.6%	130,680	31.7%	113.2%	412,220	100.1%
OR	$3,196.00	11,456	$621.09	19.4%	802	7.0%	122.4%	12,897	112.6%
PA	$3,843.79	703,080	$859.59	22.4%	388,580	55.3%	101.8%	704,780	100.2%
SC	$3,529.74	582,110	$462.80	13.1%	434,380	74.6%	110.8%	589,870	101.3%
SD	$1,414.55	1,885	$28.87	2.0%	38	2.0%	276.6%	4,215	223.6%
TN	$4,393.99	306,270	$383.81	8.7%	57,789	18.9%	89.0%	306,350	100.0%
TX	$3,194.46	921,870	$628.08	19.7%	606,090	65.8%	122.5%	928,150	100.7%
UT	$1,648.95	9,093	$236.24	14.3%	481	5.3%	237.2%	20,532	225.8%
VA	$4,929.50	642,740	$1,040.73	21.1%	538,930	83.9%	79.4%	635,650	98.9%
WA	$1,726.98	16,900	$731.53	42.4%	2,551	15.1%	226.5%	34,750	205.6%
WV	$3,691.71	1,691,100	$101.57	2.8%	283,930	16.8%	106.0%	944,670	100.2%
WI	$3,436.60	943,180	$373.50	10.9%	538,100	57.1%	113.8%	1,691,400	100.0%
WY	$1,286.52	9,406	$26.08	2.0%	144	1.5%	304.1%	25,443	270.5%
Total		18,525,885			10,711,919	57.8%		18,560,303	100.19%

The first column shows the Pigouvian price of pollution for each state, accounting for spillovers. This is the reference policy. The second column shows the resulting abatement in each state. The third column shows the price each state would choose, and the fourth the resulting abatement. The fifth and sixth columns show these prices and abatements relative to the Pigouvian. The seventh column shows the abatement occurring in each state under a federally imposed price of $3,912 per ton SO_2. The eighth and ninth show this price and induced abatement as respective shares of the reference policy.

Figure 1A. Efficiency loss with uniform pollution price: Heterogeneity in abatement benefits but not abatement costs.

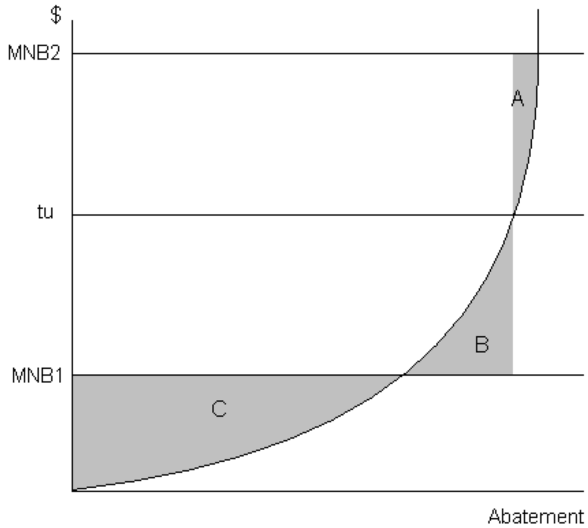


Figure 1B. Efficiency loss with uniform pollution price: Heterogeneity in abatement benefits and abatement costs.

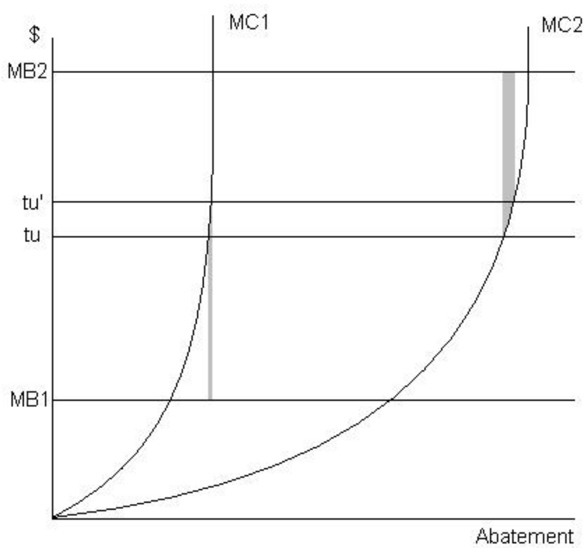


Figure 2. Marginal Abatement Cost Curves for SO_2

The dashed line represents the raw data from the electricity model, while the solid line reflects application of the Lowess smoother.

Figure 2a. Colorado.

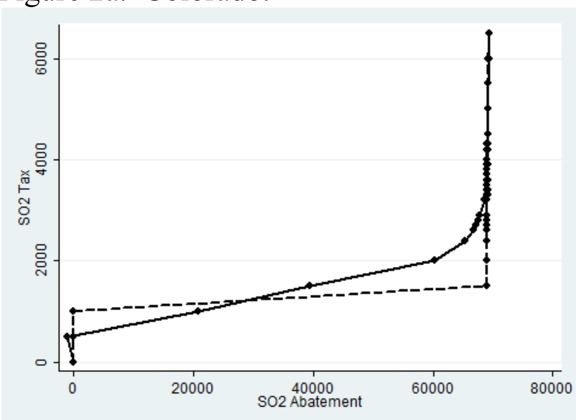


Figure 2b. New York

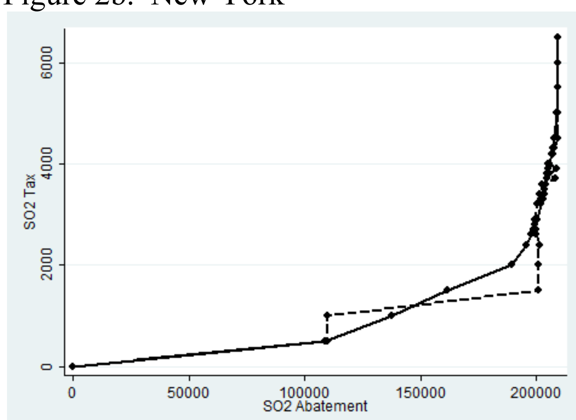


Figure 2c. Texas.

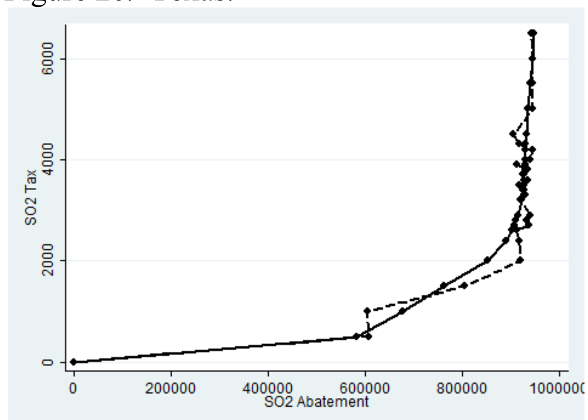


Figure 2d. Connecticut.

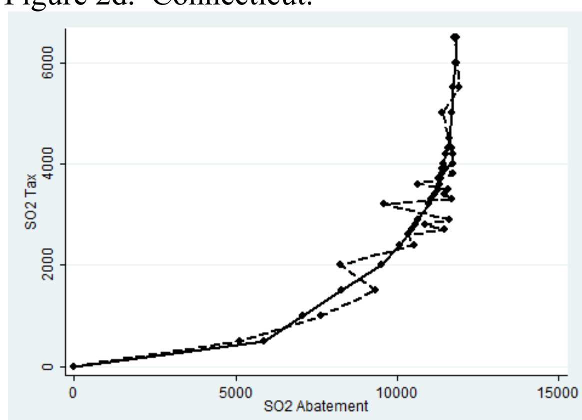


Figure 3—Marginal Cost and Marginal Benefit Curves for SO_2 Abatement

The solid line represents the marginal cost of abatement curve. The dashed line at $3912 represents the second-best uniform price. The upper of the other two dashed lines represents marginal damages from the state, and thus the Pigouvian price. The lower dashed-line represents marginal damages that fall within the respective state, and thus the price the state would select when ignoring spillovers.

Fig. 3a. Louisiana

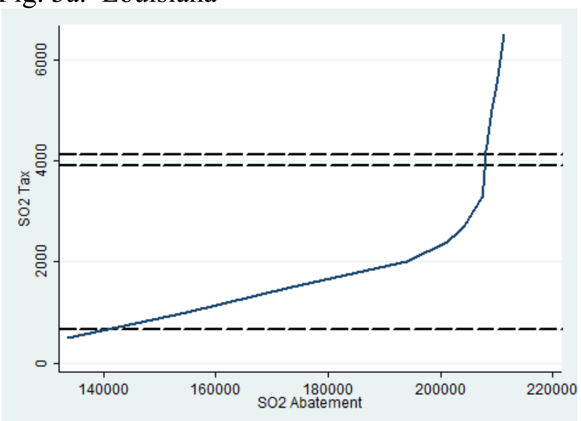


Fig. 3b. Florida

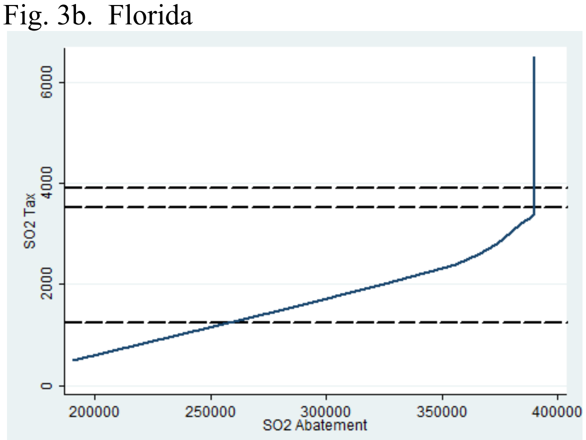


Fig. 3c. California.

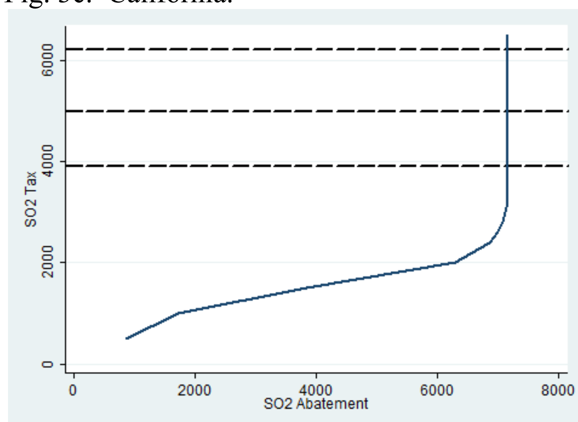


Fig. 3d. Illinois

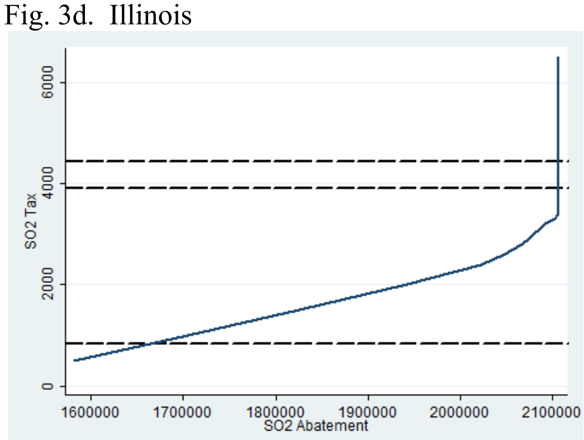
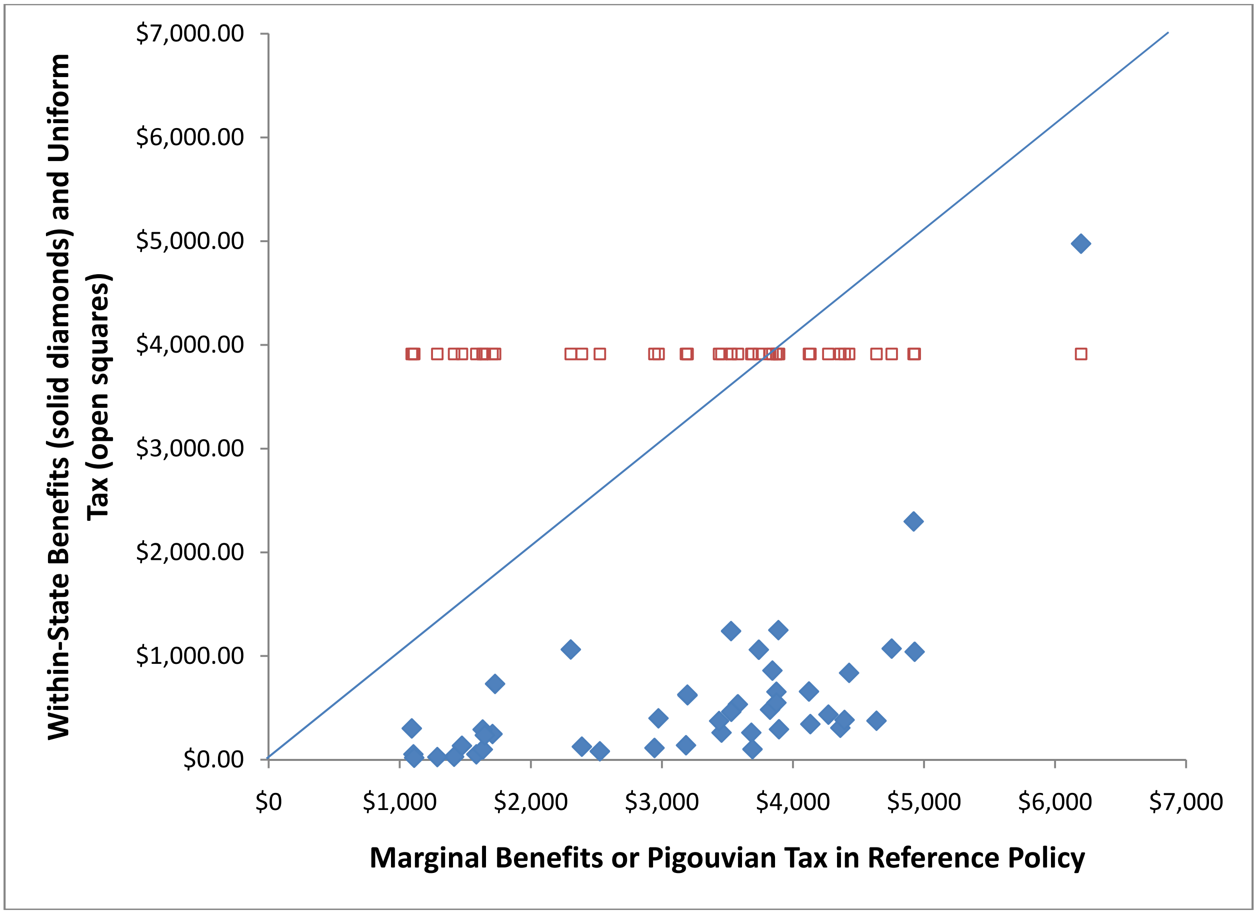
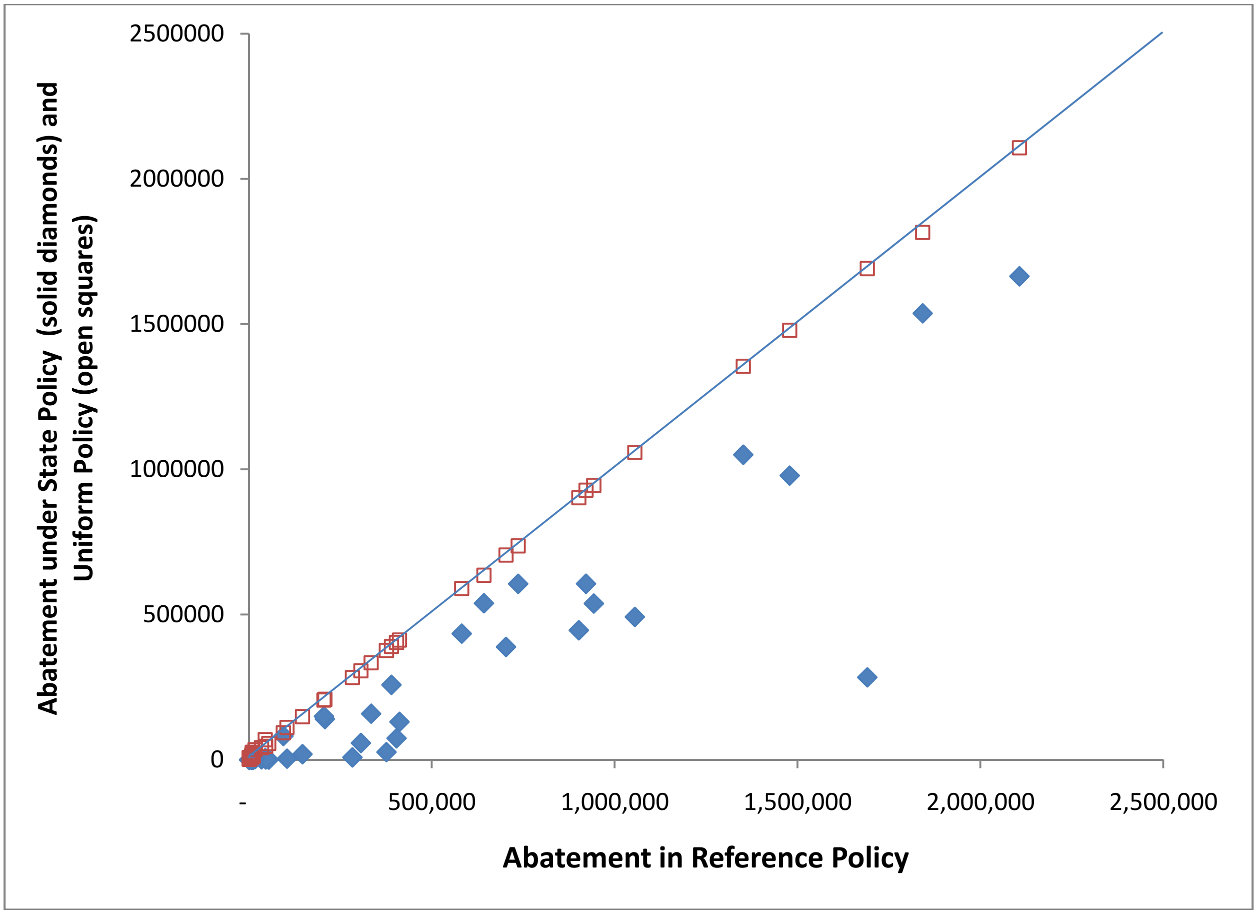


Figure 4. Pollution Prices under State and Uniform Policies vs. Reference Policy



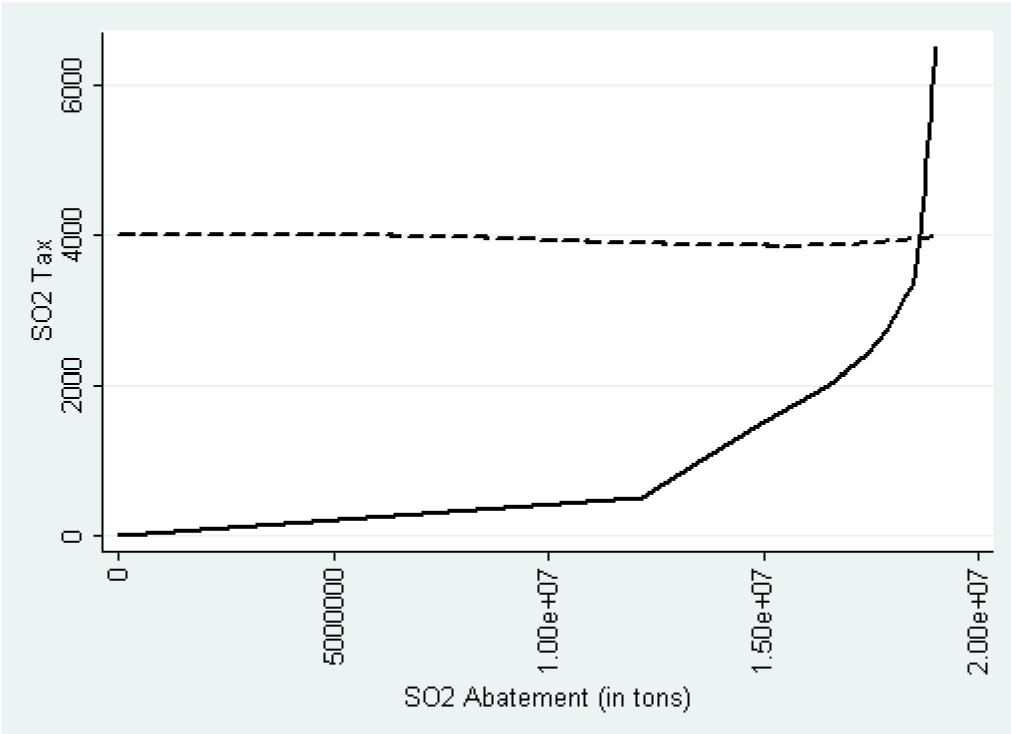
This figure shows the pollution prices chosen by states under a devolved policy (solid diamonds) as well as the uniform price of $3912 (open squares) plotted against each states' respective optimal price. Departures from the 45-degree line reflect departures from optimal prices.

Figure 5. Abatement under State and Uniform Policies vs. Reference Policy



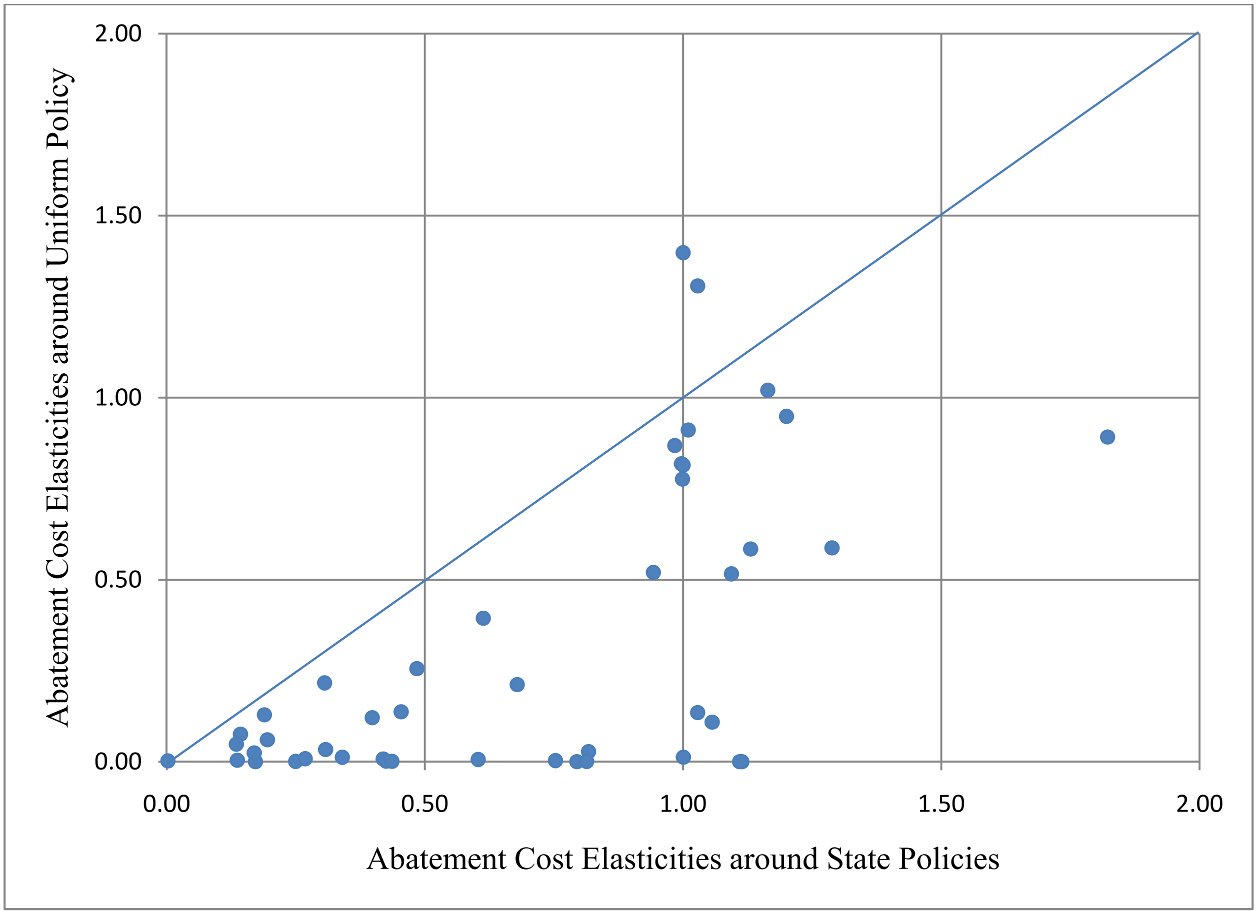
This figure shows the abatement chosen by states under a devolved policy (solid diamonds) as well as each state's abatement under the uniform pollution price of $3912 (open squares) plotted against each states' respective optimal abatement. Departures from the 45-degree line reflect departures from optimal abatement.

Figure 6—National Uniform SO_2 Policy



The dashed line represents the national marginal benefit (MB) curve for sulfur dioxide abatement. Notice that, unlike the state MB curves, this curve is not necessarily horizontal. State-specific marginal damages are constant, but since different states abate at different points in the range of abatement, the national MB curve is not constant. This line has been smoothed with the Lowess smoother. The solid line represents the national MCA curve. The point of intersection determines the efficient national uniform price, which is $3,912 per ton of sulfur dioxide.

Figure 7. Elasticities of Marginal Abatement Costs around Equilibria for State and Uniform Policies



The figure plots the elasticities in the marginal abatement cost curve near the uniform policy against the state policies. For each second-best policy, arc elasticities are computed as the percentage deviation in abatement from the reference policy divided by the percentage deviation in prices from the reference policy.

Appendix: Proof of the Propositions 1-3 and Corollary

We begin again with an indicator of total welfare:

$$W = \sum_{i=1}^{N} \left[MNB_i * A_i(t_i) - \int_0^{A_i(t_i)} MC_i(x)dx \right] \quad \text{(A1)}$$

and take a third-order Taylor approximation for changes in t_i. Using MC=t and $\frac{\partial^3 A_i}{\partial t^3}$≈0, this gives:

$$dW \approx \begin{array}{l} \sum_{i=1}^{N} \left[(MNB_i - t)\frac{\partial A_i}{\partial t} \right] dt_i - \frac{1}{2}\sum_{i=1}^{N} \frac{\partial A_i}{\partial t} dt_i^2 \\ + \frac{1}{2}\sum_{i=1}^{N} (MNB_i - t)\frac{\partial^2 A_i}{\partial t^2} dt_i^2 - \frac{1}{3}\sum_{i=1}^{N} \frac{\partial^2 A_i}{\partial t^2} dt_i^3. \end{array} \quad \text{(A2)}$$

It will be convenient to use the following additional notation using iid random variables e and u. e_i is a state's deviation from average national benefits and u_i is its spillovers ($u_i = \sum_{j \neq i} MB_{ij}$.) Let MNB_i=μ+e_i, with E[e_i]=0, E[e_i^2]=σ_e^2, E[e_i^3]=0, and $\alpha_i \perp e_i$. Let MB_{ii}=MNB_i - u_i, with u_i>0, E[u_i]=υ, E[u_i^2]= σ_u^2 and $\alpha_i \perp u_i$ and $e_i \perp u_i$. These assumptions reflect the assumptions in the text: namely, that the distribution of social benefits is symmetric, and that heterogeneity in costs and benefits are orthogonal to each other and to the cost scalings (or baseline emissions) α_i. We consider a particular draw k from the state of nature for a vector of N local jurisdictions.

We will evaluate (A2) at the uniform policy t = μ_k (and MNB_i-t =e_i) and consider the third-order approximation to the change in welfare from switching to the state policy, so dt_i= (μ_k+e_i-u_i)- μ_k =e_i-u_i. Substituting these expressions into (A2) and using $\frac{\partial A_i}{\partial t} = \frac{\partial A}{\partial t}\alpha_i$ gives:

$$dW_{sk} \approx \begin{array}{l} \frac{\partial A}{\partial t}|_\mu \sum_{i=1}^{N} \alpha_{ik} e_{ik}(e_{ik} - u_{ik}) - \frac{1}{2}\frac{\partial A}{\partial t}|_\mu \sum_{i=1}^{N} \alpha_{ik}(e_{ik} - u_{ik})^2 \\ + \frac{1}{2}\frac{\partial^2 A}{\partial t^2}|_\mu \sum_{i=1}^{N} \alpha_{ik} e_{ik}(e_{ik} - u_{ik})^2 - \frac{1}{3}\frac{\partial^2 A}{\partial t^2}|_\mu \sum_{i=1}^{N} \alpha_{ik}(e_{ik} - u_{ik})^3. \end{array} \quad \text{(A3)}$$

We can take $\partial A/\partial t$ out of the summation because it is a constant when evaluated at μ_k. First summing over i and then taking expectations over k, using the premises that $\alpha_i \perp e_i$, $\alpha_i \perp u_i$, $e_i \perp u_i$, $E[e_i^3]=0$ and $\sum \alpha_i=1$, and using the fact that $E[u^2]= \sigma_u^2 + \upsilon^2$, this expression reduces to:

$$E[dW_s] \approx \frac{1}{2}\frac{\partial A}{\partial t}|_\mu N(\sigma_e^2 - \sigma_u^2 - \upsilon^2) + \frac{1}{3}\frac{\partial^2 A}{\partial t^2}|_\mu N E[u_{ik}^3]. \quad \text{(A4)}$$

To evaluate Proposition 1, consider "scaling up" each inter-state spillover u_i by a factor $\theta>0$. Then expression (A4) becomes

$$E[dW_s] \approx \frac{1}{2}\frac{\partial A}{\partial t}|_\mu N(\sigma_e^2 - \theta^2\sigma_u^2 - \theta^2\upsilon^2) + \frac{1}{3}\frac{\partial^2 A}{\partial t^2}|_\mu N\theta^3 E[u_{ik}^3].$$

Since $\partial A/\partial t>0$ and, by the concavity of $A(t)$ (i.e. convexity of $MC(A)$), $\frac{\partial^2 A}{\partial t^2}|_\mu<0$, this expression is decreasing in θ. That is, the effect on welfare of switching from the centralized policy to the devolved policies is decreasing in inter-state spillovers.

Similarly, to evaluate Proposition 2, consider instead "scaling up" each error imposed by ignoring heterogeneity e_i by a factor $\theta > 0$. Then expression (A4) becomes

$$E[dWs] \approx \frac{1}{2}\frac{\partial A}{\partial t}|_\mu N(\theta^2\sigma_e^2 - \sigma_u^2 - \upsilon^2) + \frac{1}{3}\frac{\partial^2 A}{\partial t^2}|_\mu N E[u_{ik}^3].$$

Again, since $\partial A/\partial t>0$, this expression is increasing in θ. That is, the effect on welfare of switching from the centralized policy to the devolved policies is increasing in inter-jurisdictional heterogeneity.

Finally, to evaluate Proposition 3, note that since $E[u_{ik}^3] > 0$, expression (A4) is increasing in $\frac{\partial^2 A}{\partial t^2}$. Increasing (resp. decreasing) this term is equivalent to making $A(t)$ more convex (resp. concave), which is equivalent to making $MC(A)$ more concave (resp. convex). That is, as $MC(A)$ becomes more convex, $\frac{\partial^2 A}{\partial t^2}$ must decrease, and welfare from switching to the state policies falls. This completes the proof of the propositions.

The corollary follows from setting the mean squared errors from the two policies equal: $\sigma_e^2 = \sigma_u^2 + \upsilon^2$. In this case, expression (A4) collapses to:

$$\mathrm{E}[dWs] \;\approx\; \frac{1}{3}\frac{\partial^2 A}{\partial t^2}|_{\mu} NE[u_{ik}^3].$$

When the marginal cost curves are linear, $\frac{\partial^2 A}{\partial t^2}$=0, and welfare under the two policies is identical. When they are convex, $\frac{\partial^2 A}{\partial t^2}$ is negative, and so, since $E[u_{ik}^3] > 0$, switching from the centralized policy to the devolved policies decreases welfare. When they are concave, $\frac{\partial^2 A}{\partial t^2}$ is positive, and switching from the centralized policy to the devolved policies increases welfare. This completes the proof of the corollary.