Journal of Public Economics 96 (2012) 449–464

Contents lists available at SciVerse ScienceDirect

Journal of Public Economics

journal homepage: www.elsevier.com/locate/jpube

Fiscal federalism and interjurisdictional externalities: New results and an application to US Air pollution ☆

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ARTICLE INFO

Article history:
Received 28 August 2010
Received in revised form 4 October 2011
Accepted 8 January 2012
Available online 26 January 2012

JEL classification:
H4
H7
Q5

Keywords:
Fiscal federalism
Environmental federalism
Air pollution

ABSTRACT

The economics of fiscal federalism has identified two book-end departures from first-best provision of a public good. Local governments may respond to local conditions, but ignore inter-jurisdictional spillovers. Alternatively, central governments may internalize spillovers, but impose uniform incentives ignoring local heterogeneity. We provide a simple model that demonstrates that the choice of pricing policy also depends crucially on a third factor, the shape of marginal costs of providing the public good. If marginal costs are convex, then marginal abatement cost elasticities will be higher around the local policies. This increases the deadweight loss of those policies relative to the centralized policy, *ceteris paribus*. If they are concave, then the opposite is true.

Using a detailed simulation model of the US electricity sector, we then empirically explore these tradeoffs 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 interstate heterogeneity in this application. Second, because of the convexity of the marginal cost functions, elasticities are much lower over the range relevant to the centralized policy, dampening the distortions.

1. Introduction

Provision of a public good typically takes place in the context of a federation with several levels of government, as in the United States or the European Union. Moreover, this federal context typically involves heterogeneity in the benefits experienced from providing the public good in different local jurisdictions, as well as spillovers from a public good provided in one local jurisdiction into others. Accordingly, a first-best policy would equate, in all locations, the marginal benefits of the public good with the marginal costs. However, this blackboard solution is typically impracticable.

Since the seminal work of Oates (1972) on fiscal federalism, a central question of public finance has been which level of a federation should be assigned the provision of the public good. On one hand, local jurisdictions are likely to account for local conditions but ignore inter-jurisdictional spillovers. On the other hand, central governments may internalize those spillovers but are likely to impose a one-size-fits-all policy that ignores local conditions.[1]

Both factors appear to be empirically relevant in environmental applications. Illustrating the importance of inter-jurisdictional spillovers, Sigman (2002) finds more pollution in international rivers than comparable rivers within nations, and Sigman (2005) likewise finds more pollution in interstate rivers in the US. Similarly, Burgess et al. (2011) and McWhinnie (2009) find that natural resources are depleted more rapidly when shared by more jurisdictions. Illustrating the ability of local jurisdictions to respond to local conditions, Chupp (2011) shows that US states are more likely to regulate air pollution beyond federal requirements when their intrastate benefits are higher; Gray and Shadbegian (2004) similarly show that states' regulation of pulp and paper mills appears to respond to proxies for benefits; and Helland and Whitford (2003) find

☆ We thank Nancy Bockstael, David Evans, Paul Ferraro, Meredith Fowlie, Lawrence Goulder, Roger von Haefen, Nick Muller, Wallace Oates, Jon Rork, Vjollca Sadiraj, David Sjoquist, Roberton Williams, and Kerry Smith for comments, as well as seminar and conference participants at Camp Resources, Clemson, the CU Workshop on Environmental Economics, Illinois State University, the NBER public/environment meetings at Stanford, Resources for the Future, the University of Kentucky, the University of Maryland, and the University of Wisconsin. We thank Dallas Burtraw and Meghan McGuinness for data and for help with the RFF electricity model.

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[1] For reviews, see Alm and Banzhaf (forthcoming), Dalmazzone (2006), Levinson (2003), and Oates (1999, 2002a). But see Ogawa and Wildasin (2009) for a special case in which decentralized policies may be optimal even with spillovers.

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doi:10.1016/j.jpubeco.2012.01.001

states are more lax about pollution near their borders than in their interiors. And in an intriguing study of both sides of the coin, Sigman (2011) finds that long-lived water pollutants—those for which spillovers are the greatest concern—are lower in nations with more centralized governments, while all water pollutants have higher intra-national variation in nations with more federal governments.

These trade-offs represent the Scylla and the Charybdis of fiscal federalism. As Oates (2002a) summarized in the context of an environmental public good:

> [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 extends the traditional benefit-side factors of heterogeneity and spillovers to important interactions with the supply side of public goods. In particular, it identifies a third factor: the more convex the marginal cost of supplying the public good, the 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 fifty years: ambient air pollution.

We begin with a simple model of a public good in a federation. The model includes heterogeneous marginal benefits of the good, inter-jurisdictional spillovers in benefits, and heterogeneity in the shapes of marginal cost (i.e. supply) functions. Regulation involves setting price incentives for providing the public good. In the specific context of our air pollution example, these prices can be interpreted as Pigovian taxes on pollution or, equivalently, because there is no uncertainty, they can be thought of as the price under a tradable pollution quota. More generally, the price could be interpreted as a unit subsidy for providing any public good, including education, public safety, transportation services, etc.

Analogous to the theory of optimal taxation, we show that the deadweight loss from errors in prices, whether from ignoring inter-state spillovers or from ignoring heterogeneity, depends in part on the slopes of the supply curves over the region of the error. If they are highly inelastic, deadweight loss from errors in prices will be small. This simple insight has an important—and to our knowledge previously unnoted—implication for fiscal federalism. Simply put, if (1) the devolved policy involves the mistake of systematically *under*-pricing the public good (because of ignoring inter-jurisdictional spillovers); (2) the centralized policy involves the mistake of *noise* around the optimal prices (from imposing some average price), and (3) the marginal cost function is convex, then the marginal cost function will tend to be more elastic in the region of the devolved policy. (The opposite is true when the marginal cost function is more concave.) Ceteris paribus, this tends to give an edge to centralization when marginal cost functions are convex and an edge to devolution when the marginal cost functions are concave.

After establishing these theoretical relationships, 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.[2] 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 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, 2011). The devolved policies lose 31.5% of those potential benefits. However, the second-best uniform policy loses only 0.2%. 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 varies by 6-fold. 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, with the difference arising because of the convexity of marginal abatement costs.

In addition to our theoretical contributions, our welfare analysis is to our knowledge the first to consider *both* sides of the environmental federalism dilemma for a major policy from a normative perspective. 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 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 et al. (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 et al. (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

[2] Besides being an important public good with large benefits, US air quality is a fitting case study in other respects as well. Institutionally, air policy involves a federal structure, with Washington setting air pollution regulations and state governments enforcing them. And historically, policies were centralized following impatience with state governments. Yet 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-controlled, so it was not necessarily in states' interests to reduce enforcement.

[3] This policy may be thought of roughly as the "first best", though it ignores within-state spatial heterogeneity in damages. Additionally, we abstract from the issue of pre-existing taxes on capital and labor (see Goulder et al., 1999 and Parry, 2005).

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 is our assumption that governments act to maximize aggregate welfare in their jurisdiction. While this is the central finding of the fiscal federalism literature (Oates and Schwab, 1988), departures from this central case are possible from a wide variety of government failures. A long literature discusses the possibility of either a "race to the bottom" or a "race to the top" under a variety of political economy conditions (e.g. Kunce and Shogren, 2005; Levinson, 2003; Markusen et al., 1995; Oates and Schwab, 1988, 1996; Wellisch, 1995). More recently, Williams (2010) point out that local jurisdictions' incentives depend on the form of the central government's policies. We abstract from these issues. In this sense, our empirical results should be thought of as isolating the classical factors driving the assignment of public good provision, rather than as predictive of what governments would actually do.

2. Theoretical model

We begin with a simple model of providing a public good in a federation using price incentives. The model applies to any public good, not just to our empirical example of abating emissions of air pollutants (i.e. providing air quality). The public good G_i in each state $i = 1\ldots N$ has constant marginal national benefits MNB_i. Constant marginal benefits implies that within-state benefits are independent of inter-state spillovers and, hence, actions in other states.[4]

These benefits can be written as the sum of the benefits for each state j from providing the public good in i: $MNB_i = \sum_j MB_{ij}$. It will be convenient to use b_i as a shorthand for within-state benefits, $b_i = MB_{ii}$, and s_i for spillovers from i into other states j, $s_i = \sum_{j \neq i} MB_{ij}$. For simplicity, we assume that within-state benefits are uncorrelated with externalities.[5] For ease of presentation, we also assume in the text that the distribution of benefits is symmetric. This assumption is not crucial, and we provide more general results involving skewness in the appendix.

Finally, each state has a non-decreasing marginal cost of abatement function $MC_i(G_i)$, with $MC_i(0) = 0$ and $MC'_i(G_i) \geq 0$. Inverting the marginal cost function gives the level of supply of the public good at any price $G_i(p_i)$. For simplicity, we assume this function may be approximated by a quadratic, so that third and higher orders can be ignored: $\frac{d^3G}{dp^3} \approx 0$.[6] Heterogeneity in these marginal cost functions is represented by differences in their slopes. We focus on these slopes for two reasons. First, our assumption that $MC(0) = 0$ implies there are no differences in the intercept of the marginal cost function. Second, it is the slopes that enter expressions for deadweight loss, so they contain the relevant economic information.

A general way to model this is to suppose that all marginal cost curves can be written $MC_i(G_i) = MC(G/\alpha_i)$, so the inverse marginal cost curves can be written $G_i(p) = \alpha_i G(p)$. Without loss of generality, we arbitrarily choose the reference curve $G(p)$ so that $\sum_i \alpha_i = 1$. This structure subsumes a number of special cases. For example, it is consistent with supply curves of a public good that are all rays out of the origin.

More interestingly for our empirical application to air quality, this structure 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 $[0, \bar{G}_i]$, where $\bar{G}_i$ represents maximal or 100% abatement in state i. In that case, $\alpha_i = \bar{G}_i / \sum_j \bar{G}_j$, the (renormalized) baseline emissions level.[7] 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. Under this particular interpretation, the parameter α_i represents baseline emissions.

Policies involve choosing a vector of prices for purchasing the public good $(p_1\ldots p_N)$. In our air pollution example, these may be thought of as Pigovian taxes or market prices in a generalized cap-and-trade system.

2.1. First-best policy

The total potential gains from choosing a vector of prices $(p_1\ldots p_N)$ is

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

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 costs of supplying the public good.

The first order conditions are:

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

Thus, the first-best policy simply equates marginal national benefits to marginal costs in each state.

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:

$$MB_{ii}{}^*G_i(p_i) + \sum_{j\neq i} MB_{ij}G_j\left(p_j\right) - \int_0^{G_i(p_i)} MC_i(x)dx. \tag{3}$$

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

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

This allows for heterogeneity of within-state benefits in the same way as the first-best policy, but departs from the first-best in ignoring inter-state spillovers. Since $MB_{ii} \leq MNB_i$, states under-provide the public good.

To a third-order approximation, the deadweight loss from moving from the first-best to the state policy is:

$$DWL_s \approx \frac{1}{2}\sum_{i=1}^{N}\frac{\partial G}{\partial p}\alpha_i(MB_{ii} - MNB_i)^2 + \frac{1}{3}\sum_{i=1}^{N}\frac{\partial^2 G}{\partial p^2}\alpha_i(MB_{ii} - MNB_i)^3 \geq 0. \tag{5}$$

(See the appendix for a derivation.) Evidently, this loss shrinks to zero as $MB_{ii} \to MNB_i$. That is, if all benefits are captured within-state, there are no inter-jurisdictional spillovers for the central government to internalize, and the local polices are equivalent to the first-best policy.

The importance of spillovers in the relative performance of local jurisdictions is well understood in the literature. However, the literature has not previously noted the second-order effect of the way spillovers interact with the curvature of the supply curve. Noting that $\partial^2 G/\partial p^2$ is negative when the marginal cost function is convex, the effect of spillovers is accentuated as the marginal abatement cost function becomes

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[4] This is a common assumption for studies of air pollution (e.g. Desvousges et al., 1998; Muller and Mendelsohn, 2007, 2009; Rowe et al., 1996). We also 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.

[5] The assumption that the two types of benefits are uncorrelated appears to be approximately true in our application, where the correlation is −0.04.

[6] This assumption plays no substantive role in the model, but simplifies the presentation.

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

more convex (or mitigated as it becomes more concave). As spillovers increase, the states' pricing policies move down the marginal abatement cost curve. When marginal costs are convex, they thus move into a region where the supply curve is more elastic, accentuating the deadweight loss. As we shall see in our empirical example, this effect can be substantial.

2.3. Uniform policy

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

The net benefits of this policy are

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

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

$$\frac{\partial G}{\partial p}\sum_{i=1}^{N}\alpha_i(MNB_i-p_u)=0. \tag{7}$$

The term $\partial G/\partial p$ can be factored out of the summation as it is a constant for all states when evaluated at the constant p_u. Dividing by $\partial G/\partial p$ and using $\sum\alpha_i=1$ gives

$$p_u^{*}=\sum_{i=1}^{N}\alpha_i MNB_i. \tag{8}$$

The second-best uniform price is a weighted average of each state's first-best prices. The weights are the cost scalings.

To fix ideas, consider our application to air pollution. At first glance, it may appear that Eq. (8) says nothing more than that large polluters carry more weight. However, this is only because high-polluting states (with high $\bar{G}_i$) 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 have no effect on the optimal price.

This intuition is clear from the formula for deadweight loss relative to the first-best. To a third-order approximation, the deadweight loss of the uniform policy, relative to the first best, is:

$$DWL_u\approx\frac{1}{2}\frac{\partial G}{\partial p}\sum_{i=1}^{N}\alpha_i\left(MNB_i-p_u^{*}\right)^2+\frac{1}{6}\frac{\partial^2 G}{\partial p^2}\sum_{i=1}^{N}\alpha_i\left(MNB_i-p_u^{*}\right)^3. \tag{9}$$

(See the appendix for a derivation.) Substituting in the above expression for $p_u{}^{*}$, using our (sufficient) condition that benefits are symmetric, and re-arranging slightly gives:

$$\begin{aligned}DWL_u\approx&\frac{1}{2}\frac{\partial G}{\partial p}\sum_{i=1}^{N}\alpha_i\left(MNB_i-\sum_{j=1}^{N}\alpha_j MNB_j\right)^2\\&+\frac{1}{6}\frac{\partial^2 G}{\partial p^2}\sum_{i=1}^{N}\alpha_i\left(MNB_i-\sum_{j=1}^{N}\alpha_j MNB_j\right)^3=\frac{1}{2}\frac{\partial G}{\partial p}\hat{\sigma}^2,\end{aligned} \tag{10}$$

where $\hat{\sigma}^2$ is the *weighted* empirical variance of the *MNB*, where the weights are the cost-scalings α_i. (See the appendix for a derivation without invoking symmetry.) This expression says that 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 ($\hat{\sigma}=0$), then this policy is equivalent to the first best.

Again, the importance of such heterogeneity generally is well-established in the fiscal 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 $p_u{}^{*}$, the decrease in welfare from the first best is scaled in Eq. (9) by $\frac{dG}{dp}\alpha_i$, the slope of the marginal cost curve. Thus, if the marginal cost curve is highly inelastic, the distortion will be small.[8] The second-best uniform policy takes this into account, as seen in Eq. (7).

Fig. 1a and b illustrates 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 policy proceeds by setting $p_u{}^{*}$ equal to the simple average of the two *MNB* levels, equating the marginal deadweight loss in each state (marked as areas A and B in the figure). (Although the totals are different, the derivative of deadweights losses A and B with respect to p are identical.) The second panel is the same except that $\overline{G}_1<\overline{G}_2$:. For example, State 1 may have low baseline pollution emissions and so its marginal cost curve becomes inelastic at lower levels of abatement. If p_u were set at the same level as before, the marginal deadweight loss of raising the price would be much lower around State 1 than the marginal welfare gains around State 2, because of the relative elasticities of the marginal cost curves. Total welfare could be increased by raising p_u closer to MNB_2. For example, the trapezoids in Fig. 1b show the respective welfare gain in State 2 and loss in State 1 of increasing the pollution price to $p_u^{'}$, 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 costs still holds.

2.4. Comparison of policies

Having discussed the two deviations from the first best, we are now in a position to compare them directly. In particular, it can be shown that, to a third order approximation, a switch from the uniform policy to the devolved policy is associated with the following change in welfare:

$$dW\approx\frac{1}{2}N\frac{\partial G}{\partial p}\left(\hat{\sigma}_b^2-\hat{\mu}_s^2\right)+\frac{1}{3}N\frac{\partial^2 G}{\partial p^2}\hat{\mu}_s^3, \tag{11}$$

where $\hat{\sigma}_b^2$ is the empirical weighted variance in within-state benefits and $\hat{\mu}_s$ is the weighted mean of spillovers. Again, the cost scaling α_i are the weights. (See the appendix.)

This analysis has a very important implication for public policy in a federation. In particular, it implies the following three federalism propositions hold.

Proposition 1. *As spillovers go to zero, $\sum_{i=1}^{N}(MNB_i-MB_{ii})\to 0$, decentralized policies approach the first best. Additionally, ceteris paribus, a marginal reduction in spillovers improves the welfare effect of decentralization relative to the centralized policy.*

[8] 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 $p_u{}^{*}$ and MNB_i.

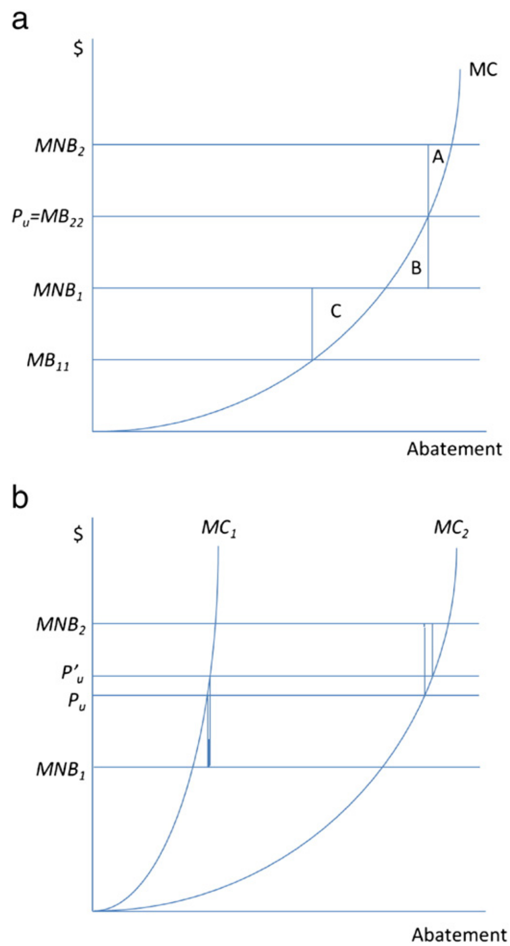

Fig. 1. A. Efficiency loss with uniform pollution price: Heterogeneity in marginal benefits but not marginal costs. B. Efficiency loss with uniform pollution price: Heterogeneity in marginal benefits and marginal costs.

Proposition 2. *As heterogeneity in overall benefits goes to zero,* $\sum_{i=1}^{N}(MNB_i - \overline{MNB})^2 \rightarrow 0$, *the centralized policy approaches the first best. Additionally, ceteris paribus, a marginal reduction in the variance of* within-state *marginal benefits improves the welfare effect of the centralized policy relative to decentralization.*

Proposition 3. *Ceteris paribus, as supply functions for public goods become more convex (concave), the centralized policy yields a higher (lower) level of welfare relative to decentralized policies.*

Proof. *See the appendix.*

The first two propositions are standard in the literature (e.g. Oates, 1972, 1999, 2002a). We include them here for completeness and to show that our model remains consistent with the standard intuition. Our one contribution to the literature in these two propositions may be the subtle but important point that it is heterogeneity in *within-state* benefits which drives the comparison between devolved and centralized policies (Proposition 2). Local jurisdictions respond to local within-state benefits, but both policies ignore heterogeneity in spillovers. To our knowledge, the literature has not recognized this distinction.

The third proposition is entirely 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 in Fig. 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 the wedge between the uniform price and optimal prices: thus, $MNB_2\text{-}p_u^* = MNB_2\text{–}MB_{22} = p_u^* - MNB_1 = MNB_1\text{–}MB_{11}$. The central government of course chooses p_u^* with deadweight loss A + B, as before. The local jurisdictions choose $p_2 = MB_{22}$ and $p_1 = MB_{11}$, 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.[9]

This example suggests another, somewhat stronger way to restate 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*

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

noting that $p_u^* = \hat{\mu}_{MNB}$. *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 cost curves are respectively convex, linear, or concave.*

Proof. See the appendix.

3. Electricity and Air pollution models

We illustrate the importance of all three factors for one of the most important policy applications for environmental federalism in the United States: inter-state air pollution. Air pollution is an apt area of application for two reasons. First, the stakes of air pollution policies are large, with estimated annual direct compliance costs of $53 billion and high benefit-cost ratios (US EPA, 2011). Second,

[9] Building on Weitzman (1974), Oates (1997) shows that the welfare loss from imposing a uniform *quantity* standard depends on the relative slops of the marginal benefit and cost curves. However, it is not clear how convexity in supply curves affects this comparison. It might seem that if governments are setting quantities of the public good instead of prices, then more convex marginal costs would favor devolution. In fact, this is not necessarily so. Fig. 1A is 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. The central government would simply set the quantity in each jurisdiction associated with p_u again, outperforming the local policies. The problem is that 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 et al., 1989).

historically the level of government controlling standards, prices, and enforcement has been a matter of debate. Accordingly, the lessons learned from this example have natural applications in other contexts as well, such as the European Union.

Our empirical methodology follows the approach taken by Banzhaf et al. (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 accommodate Pigovian taxes on pollution or pollution caps.

Using these supply and demand inputs, the model solves for electricity quantities and prices and pollution byproducts. 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.

Importantly, under scenarios with low-pollution prices the model estimates counterfactual scenarios, effectively reversing many of the observed real-world pollution investments made under the Clean Air Act. For example, the model removes post-combustion controls like scrubbers, observed in the status quo, in these counterfactuals.

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 emissions from any of 10,000 sources in the US. Rowe et al. (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 Associates, 2008).

TAF consists of several modules, each of which was developed by a team of experts in their respective field.[10] 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 and population patterns 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.[11] 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, 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 $6.3 million (in 2000 dollars) used by the EPA in its benefit-cost analysis (US EPA, 2011). 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

[10] See Lumina Decision Systems (2009) and Argonne National Laboratory (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.

[11] 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).

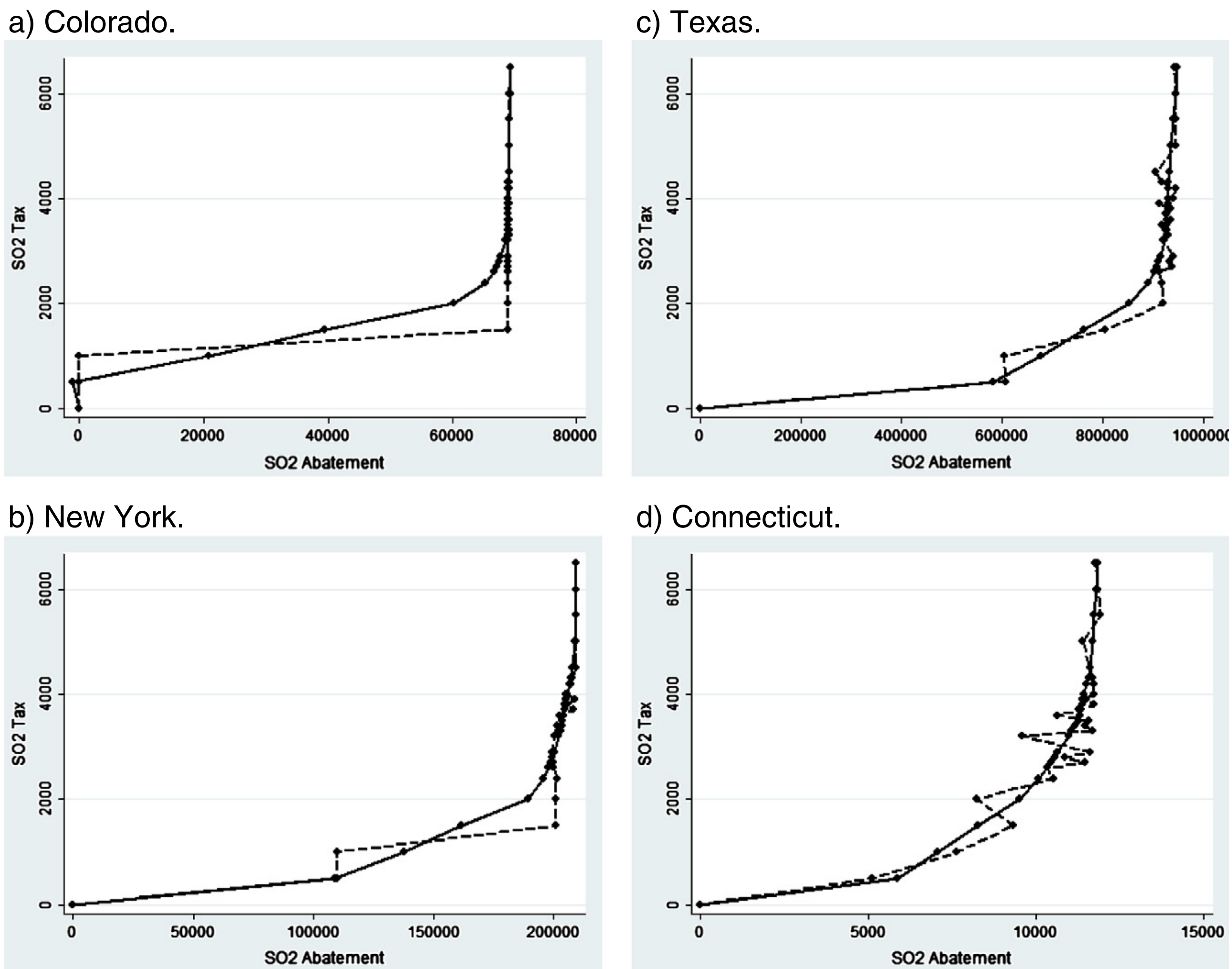

Fig. 2. Marginal abatement cost curves for SO_2. The dashed line represents the raw data from the electricity model, while the solid line reflects application of the Lowess smoother.

in the following way. We compute these latter policies for 45 of the 48 continental states.[12]

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 baseline is a simulated scenario 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 higher electricity prices.[13]

We emphasize that there is nothing about this procedure that limits its applicability to only Pigovian 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.[14] 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

[12] 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.

[13] 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. Adoption of scrubbers and switching to low-sulfur and natural gas are the primary adjustments. Electricity prices increase about 6% and electricity output falls about 1%.

[14] On the treatment of such leakage in US regional policies, see Burtraw et al. (2006), Farnsworth et al. (2008), and Sue Wing and Kolodziej (2009).

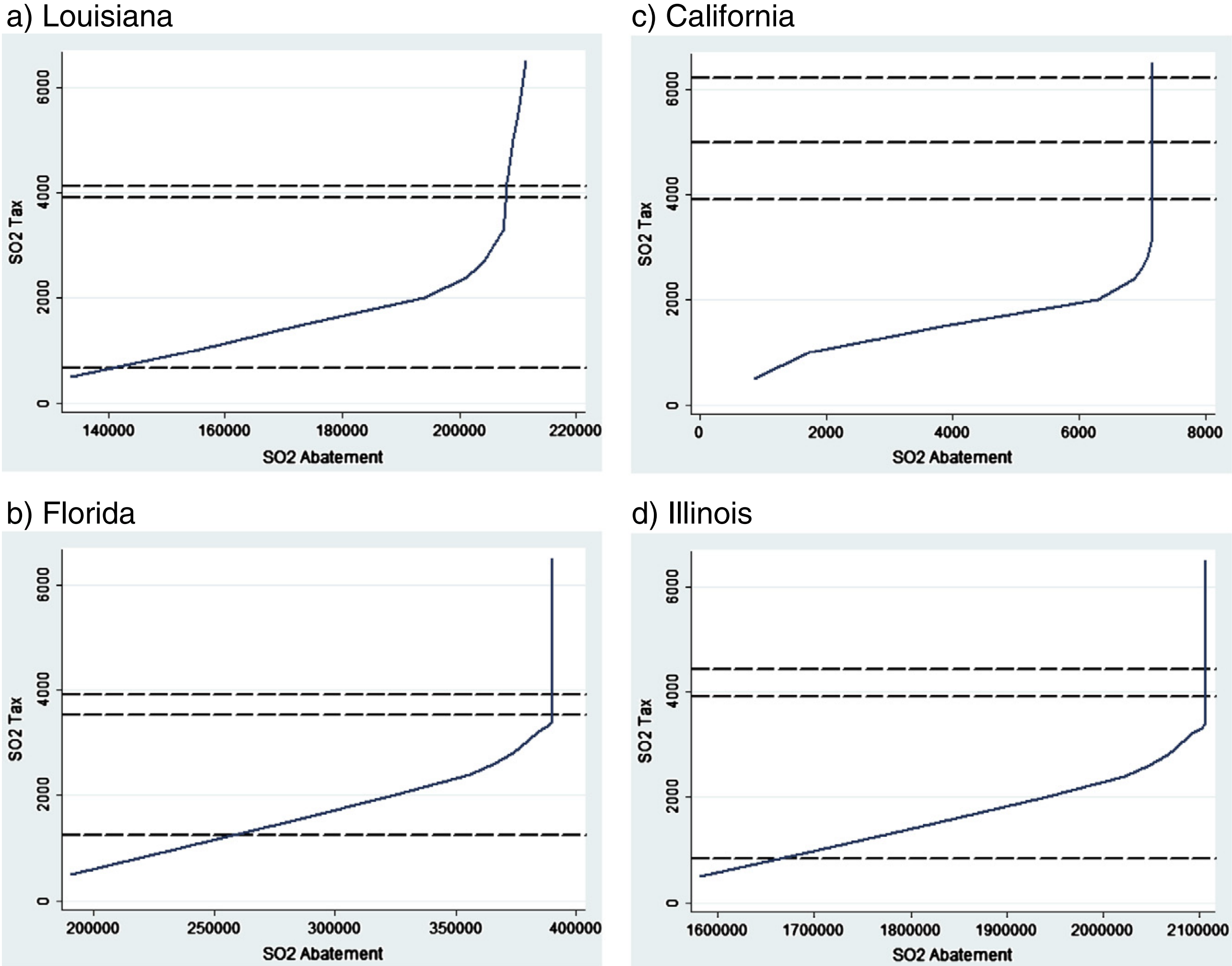

Fig. 3. Marginal cost and marginal benefit curves for SO_2 abatement.The solid line represents the marginal cost of abatement curve. The dashed line at $3912 represents the second-best uniform price. The upper of the other two dashed lines represents marginal damages from the state, and thus the Pigovian 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.

total pollution cap (Farnsworth et al., 2008). 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.) Though we view this approach as the most policy-relevant and the closest in spirit to the theoretical model, the sensitivity of our results to this approach is an open question.

The information that is observed from the electricity model is a sequence of price-pollution pairs. Fig. 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 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.[15] We impose some smoothness on the data because the raw data for some small states like Connecticut, shown in Fig. 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.[16] 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 Fig. 2b and c) or non-existent (e.g. Colorado shown in Fig. 2a). (Note that 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 finding is not surprising in this application, where the supply of the public good is a *reduction* in pollution emissions (see Keohane, 2006 for a similar finding). Since they are non-negative, once emissions fall to zero further reductions are impossible, no matter how

[15] 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.

[16] 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.

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.

high the pollution prices. Tautologically, the marginal cost of abatement must be infinite at zero emissions (100% abatement).[17] Nevertheless, this fact has important implications. 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 p_u*. Because their abatement benefits tend to be lower, this raises p_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.

Fig. 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 p_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 Fig. 3. If marginal benefits of abatement were uniform within states, this policy would be the first best.[18]

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 Pigovian 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 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

[17] Note this does not imply that *total* costs of any policy approach infinity at the same rate. To the contrary, relative to a linear marginal cost curve these convex marginal cost curves imply relatively low inframarginal abatement costs. It is only near 100% abatement that *marginal* costs become very high. But even when this region becomes relevant because of high prices, total costs are not necessarily extraordinarily high because only small changes in emissions are achieved in this neighborhood. By the same token, locally high marginal costs of pollution abatement per se do not necessarily imply high marginal costs of electricity, since at this margin electricity is produced cleanly (with natural gas or renewable). Indeed, though marginal abatement costs are highly inelastic around the prices in our reference scenario, electricity prices increase only about six percent.

[18] Muller and Mendelsohn (2009) and Fowlie and Muller (2010) show that within-state heterogeneity in benefits can be substantial. However, since our goal here is to compare policy decisions at local and national jurisdictions, this reference policy is the appropriate standard of comparison, not a fully plant-level-differentiated first best.

Table 2
Marginal SO_2 abatement costs (or pollution price) and associated abatement levels.

State	A Pigovian price (2000 $)	B Pigovian abatement (tons)	C State-policy price (2000 $)	D State price as % of Pigovian	E State level abatement (tons)	F State abatement as % of Pigovian	G $3912 uniform tax as % of Pigovian	H Uniform price abatement (tons)	I Uniform abatement as % of Pigovian
AL	$4133.10	283,160	$343.58	8.3%	8335	2.9%	94.7%	283,160	100.0%
AZ	$1707.51	7466	$247.80	14.5%	1088	14.6%	229.1%	14,004	187.6%
AR	$4637.93	334,470	$375.59	8.1%	158,670	47.4%	84.3%	334,040	99.9%
CA	$6199.27	7156	$4975.46	80.3%	7127	99.7%	63.1%	7149	99.9%
CO	$1632.33	44,902	$291.53	17.9%	6061	13.5%	239.7%	69,091	153.9%
CT	$3739.77	11,353	$1060.46	28.4%	7225	63.6%	104.6%	11,415	100.5%
DE	$2526.79	146,720	$81.56	3.2%	19,444	13.3%	154.8%	148,490	101.2%
FL	$3528.00	389,960	$1240.30	35.2%	257,900	66.1%	110.9%	390,020	100.0%
GA	$3825.17	902,190	$482.79	12.6%	445,870	49.4%	102.3%	902,220	100.0%
IL	$4428.95	2,107,100	$837.04	18.9%	1,664,600	79.0%	88.3%	41,494	119.6%
IN	$4271.14	1,478,700	$435.29	10.2%	978,530	66.2%	91.6%	2,107,100	100.0%
IA	$3184.11	34,705	$139.51	4.4%	1800	5.2%	122.9%	1,478,600	100.0%
KS	$2943.90	54,528	$113.87	3.9%	616	1.1%	132.9%	56,226	103.1%
KY	$4362.10	403,580	$307.69	7.1%	74,165	18.4%	89.7%	403,800	100.0%
LA	$4122.66	208,060	$657.81	16.0%	140,300	67.4%	94.9%	207,970	100.0%
ME	$1091.30	2605	$302.32	27.7%	1263	48.5%	358.5%	4094	157.1%
MD	$3874.41	736,320	$654.99	16.9%	605,860	82.3%	101.0%	736,350	100.0%
MA	$2304.91	10,954	$1063.06	46.1%	6568	60.0%	169.7%	12,223	111.6%
MI	$3580.13	1,352,700	$534.50	14.9%	1,050,300	77.6%	109.3%	1,354,900	100.2%
MN	$2973.92	12,275	$399.84	13.4%	727	5.9%	131.5%	16,239	132.3%
MS	$3893.92	46,223	$293.67	7.5%	1090	2.4%	100.5%	46,223	100.0%
MO	$3682.91	376,200	$260.87	7.1%	26,545	7.1%	106.2%	376,480	100.1%
MT	$1104.10	925	$52.39	4.7%	31	3.4%	354.3%	5967	645.4%
NE	$1584.08	10,996	$52.60	3.3%	382	3.5%	247.0%	22,663	206.1%
NV	$2389.29	104,360	$126.13	5.3%	4054	3.9%	163.7%	111,400	106.7%
NH	$1474.36	7488	$134.77	9.1%	226	3.0%	265.3%	12,872	171.9%
NJ	$4922.04	94,464	$2297.02	46.7%	81,956	86.8%	79.5%	93,173	98.6%
NM	$1633.95	934	$99.16	6.1%	84	9.0%	239.4%	1441	154.3%
NY	$3889.20	205,350	$1249.50	32.1%	149,600	72.9%	100.6%	205,610	100.1%
NC	$4753.78	1,842,500	$1071.42	22.5%	1,537,000	83.4%	82.3%	1,815,600	98.5%
ND	$1109.55	958	$19.34	1.7%	17	1.7%	352.6%	7767	810.5%
OH	$3874.56	1,055,500	$549.61	14.2%	491,990	46.6%	101.0%	1,058,100	100.2%
OK	$3455.63	412,000	$261.44	7.6%	130,680	31.7%	113.2%	412,220	100.1%
OR	$3196.00	11,456	$621.09	19.4%	802	7.0%	122.4%	12,897	112.6%
PA	$3843.79	703,080	$859.59	22.4%	388,580	55.3%	101.8%	704,780	100.2%
SC	$3529.74	582,110	$462.80	13.1%	434,380	74.6%	110.8%	589,870	101.3%
SD	$1414.55	1885	$28.87	2.0%	38	2.0%	276.6%	4215	223.6%
TN	$4393.99	306,270	$383.81	8.7%	57,789	18.9%	89.0%	306,350	100.0%
TX	$3194.46	921,870	$628.08	19.7%	606,090	65.8%	122.5%	928,150	100.7%
UT	$1648.95	9093	$236.24	14.3%	481	5.3%	237.2%	20,532	225.8%
VA	$4929.50	642,740	$1040.73	21.1%	538,930	83.9%	79.4%	635,650	98.9%
WA	$1726.98	16,900	$731.53	42.4%	2551	15.1%	226.5%	34,750	205.6%
WV	$3691.71	1,691,100	$101.57	2.8%	283,930	16.8%	106.0%	944,670	100.2%
WI	$3436.60	943,180	$373.50	10.9%	538,100	57.1%	113.8%	1,691,400	100.0%
WY	$1286.52	9406	$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 Pigovian 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 Pigovian. The seventh column shows the abatement occurring in each state under a federally imposed price of $3912 per ton SO_2. The eighth and ninth show this price and induced abatement as respective shares of the reference policy.

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, 2011). 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% 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![19]

[19] Our estimated gain of differentiation of just over $100 m compares to a recent estimate by Muller and Mendelsohn (2009) of $300 m to $900 m. These are of the same order of magnitude (and under 2% of first-best benefits), but the differences warrant discussion. As noted above, 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. (See also Fowlie and Muller, 2010, where lowering the over-all pollution cap shrinks the welfare loss from imposing uniform prices.) Additionally, our model has a more detailed treatment of plant-specific abatement costs, whereas Muller and Mendelsohn have a detailed treatment of plant-specific benefits. Consequently, "heterogeneity" means something different in the two applications: the gains from considering inter-plant heterogeneity will be larger than considering inter-jurisdictional heterogeneity.

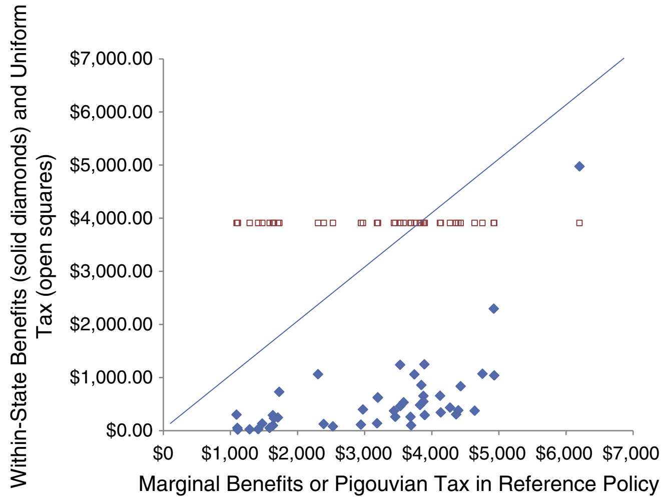

Fig. 4. Pollution Prices under State and Uniform Policies vs. Reference Policy. This figure shows the pollution prices chosen by states under a devolved policy (solid diamonds) as well as the uniform price of $3912 (open squares) plotted against each states' respective optimal price. Departures from the 45-degree line reflect departures from optimal prices.

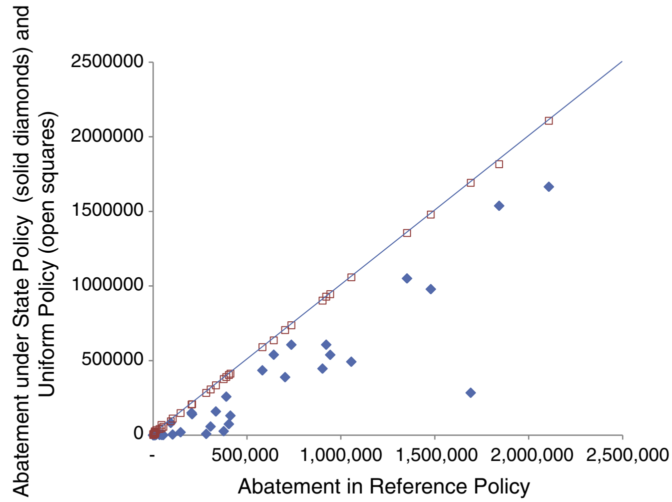

Fig. 5. Abatement under state and uniform policies vs. reference policy. This figure shows the abatement chosen by states under a devolved policy (solid diamonds) as well as each state's abatement under the uniform pollution price of $3912 (open squares) plotted against each states' respective optimal abatement. Departures from the 45-degree line reflect departures from optimal abatement.

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 Pigovian 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 optimal percentage 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.[20]

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 pollution prices 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. Fig. 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, 2011).

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

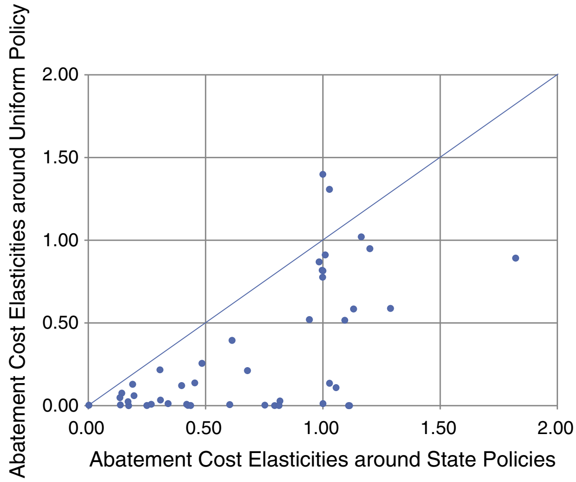

Fig. 6. Elasticities of marginal abatement costs around equilibria for state and uniform policies. The figure plots the elasticities in the marginal abatement cost curve near the uniform policy against the state policies. For each second-best policy, arc elasticities are computed as the percentage deviation in abatement from the reference policy divided by the percentage deviation in prices from the reference policy.

Finally, Column E shows the abatement under the simulated state policies and Column F shows this abatement relative to the reference policy level. Fig. 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 optimal 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. We calculate the optimal uniform pollution price to be $3912.[21] Again, this compares to an average SO_2 price in the US of $100 to $1600 prevailing in recent years.

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

Column G of Table 2 shows how this price compares to national benefits from abatement in each state. These data are also plotted in Fig. 4 (as 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 states 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.[22]

4.4. Discussion

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% 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. Fig. 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 abatement near first-best levels.

A comparison of Figs. 4 and 5 indicate that, although pricing errors are smaller under the uniform policy (Fig. 4), they also translate into even smaller errors in the level of abatement (Fig. 5). This is because they occur at higher prices on average, where the marginal abatement cost curves are more inelastic. As shown in Fig. 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 relationship identified in Proposition 3.

Fig. 6 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.[23] 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

[21] Our second-best uniform SO_2 price of $3912 compares to $3500 in Banzhaf et al. (2004). 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 straightforward and more consistent. Sensitivity analyses using their estimates suggest this would not qualitatively affect the results found here.

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

[23] That is, for the two respective 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.

Table 3
Ratio of devolved net benefits to centralized net benefits: counterfactual simulations with alternative values for spillovers, within-state heterogeneity, and convexity in abatement supply.

Shape of MC curve (see notes)	Adjustment factor for spillovers (μ_s)		
	1.00	0.50	0.105
Observed	0.639[a]	0.725	0.968
Less convex	0.691	0.796	0.985
Linear	0.751	0.877	1.000[b]
Concave	0.906	0.995	1.002

Shape of MC curve (see notes)	Adjustment factor for heterogeneity in within-state marginal benefits (σ_b)		
	1.00	1.25	1.50
Observed	0.639[a]	0.700	0.748
Less convex	0.691	0.734	0.769
Linear	0.751	0.773	0.793
Concave	0.906	0.908	0.910

The table shows the ratio of the benefits of the devolved policy to the centralized policy under different scenarios. Our model predicts that the ratio will increase as we move right in each panel (lower spillovers or more heterogeneity) and when we move down the rows within each panel (less convex/more concave supply).
With regard to the shape of the MC curve, the "observed" curve is based on a polynomial function fit by least squares to our empirical data of percentage abatement. The equation is

$$Pct\ Abatement = -0.2041679 - 0.0003504 * Price + 0.0404269 * Price^{0.5}$$

Additionally, it is linearized at the point where it would bend backward. The third ratio is based similarly on a linear function fit to our empirical data. The equation is

$$Pct\ Abatement = 0.4573211 + 0.000125 * Price.$$

The other two counter-factual supply functions are "calibrated" to intersect at the same point as the preceding two (96.2% abatement at a price of $4036). The second "less convex" function is an average of the two preceding functions. The fourth, concave function, is

$$Pct\ Abatement = 0.6 + 3.37737E{-}19 * Price^5$$

[a] This cell represents the observed scenario. The ratio of 0.639 differs slightly from the ratio in Table 1 of 0.686 because here we replace the non-parametrically estimated supply curves with parametric estimates.
[b] This scenario fits the conditions in our corollary, in which the two policies should yield equal welfare.

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 fiscal federalism literature.

To further explore these three factors, we recomputed optimal prices and resulting welfare under counterfactuals with differing levels of inter-jurisdictional spillovers and heterogeneity in within-state benefits, and with alternative supply curves featuring different curvature.[24] Table 3 shows the ratio of welfare from the decentralized policies to the centralized policy, under various scenarios. The table is organized in two panels. In each panel, the rows represent different levels of curvature, starting with our observed marginal cost curves and moving progressively less convex to linear and then concave marginal cost curves. In the first panel, the columns represent alternative adjustment factors for spillovers. In the second panel, the columns represent alternative adjustment factors for the standard deviation in within-state benefits; that is, they represent mean-preserving spreads in heterogeneity. Proposition 1 implies that, for each row, the ratio should increase as we move to the right in Panel 1, while Proposition 2 implies the same for Panel 2. Proposition 3 implies that the ratio should increase as we move down each column in each panel.

The counterfactual simulations confirm each of the propositions. Moreover, they reveal that the effect of the curvature in the marginal cost curve can be substantial. At the baseline level of spillovers and heterogeneity (i.e. column 1), moving from our observed marginal cost curve to a linearized version would improve the ratio of local to centralized policies by about 11 percentage points. To put this figure in perspective, 11% of the net benefits of the reference policy is $6.6 billion annually, a substantial sum. Perhaps more enlightening, compared to a linearized marginal cost curve, the observed curvature has about the same impact on the localized-to-centralized benefit ratio as decreasing spillovers by 50% (9 percentage points) or increasing the standard deviation in within-state benefits by 50% (11 percentage points). Nevertheless, there are other regions in the parameter space where the effect of the curvature in marginal costs is smaller, such as Panel 1, column 3, where spillovers are very low, and all ratios are close to one regardless of curvature.

4.5. 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 to fall slightly while the uniform policy benefits rise slightly, further exacerbating the difference between the two policies.[25] This result is somewhat counterintuitive. As the income elasticity rises, so does state level heterogeneity in damages. 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.

4.6. 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.

[24] For tractability, we replace the non-parametrically estimated marginal cost curves with parametric estimates, which allows for closed-form solutions to their integrals. Interstate-heterogeneity is restricted to take the form of Section **2** (i.e. differing only in the parameter α, and the model is fit to the data over the relevant range of the three policies. The R^2 is 0.78, indicating a good fit to the data, and re-simulating the base scenario results in welfare estimates within 5% of the original estimates, indicating little sensitivity to this alteration.

[25] Results 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 fiscal 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 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 first best, in fact the US federal government has not actually adopted anything like this policy, despite having forty years since the passage of the first Clean Air Act to get it right. This discrepancy raises 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.

Appendix A. Proof of the Propositions 1–3 and corollary

Preliminaries

We begin again with an indicator of total welfare:

$$W=\sum_{i=1}^{N}\left[MNB_i*G_i(p_i)-\int_0^{G_i(p_i)}MC_i(x)dx\right] \tag{A1}$$

and take a third-order Taylor approximation for changes in p_i. Using $MC=p$, this gives:

$$dW\approx\sum_{i=1}^{N}(MNB_i-p_i)\frac{\partial G_i}{\partial p}dp_i-\frac{1}{2}\sum_{i=1}^{N}\frac{\partial G_i}{\partial p}\,dp_i^2+\frac{1}{2}\sum_{i=1}^{N}(MNB_i-p_i)\frac{\partial^2 G_i}{\partial p^2}dp_i^2-\frac{1}{3}\sum_{i=1}^{N}\frac{\partial^2 G_i}{\partial p^2}dp_i^3 \tag{A2}$$

If we evaluate Eq. (A2) at the first best, where $p_i=MNB_i$, then Eq. (A2) simplifies to

$$dW\approx-\frac{1}{2}\sum_{i=1}^{N}\frac{\partial G_i}{\partial p}\,dp_i^2-\frac{1}{3}\sum_{i=1}^{N}\frac{\partial^2 G_i}{\partial p^2}dp_i^3. \tag{A3}$$

Eq. (5) in the text can be derived simply by substituting $dp_i=MB_{ii}-MNB_i$.

To consider the uniform policy, we will evaluate Eq. (A2) around that policy and consider a change to the first best. In this case, $dp_i=(MNB_i-p_i)=(MNB_i-p_u)$. Consequently, Eq. (A2) simplifies to Eq. (9) in the text.

Using $A\partial G_i/\partial p=\alpha_i(\partial AG/\partial p)$ and factoring out $\partial AG/\partial p$, which is the same in all jurisdictions when evaluated at the uniform price, and substituting for dp, this becomes:

$$dW\approx\frac{1}{2}\frac{\partial G}{\partial p}\sum_{i=1}^{N}\alpha_i\,(MNB_i-\hat{\mu}_{MNB})^2+\frac{1}{6}\frac{\partial^2 G}{\partial p^2}\sum_{i=1}^{N}\alpha_i(MNB_i-\hat{\mu}_{MNB})^3. \tag{A5}$$

Using $\sum\alpha=1$ and summing gives:

$$dW\approx\frac{1}{2}N\frac{\partial G}{\partial p}\hat{\sigma}^2_{MNB}+\frac{1}{6}N\frac{\partial^2 G}{\partial p^2}\left(\hat{\gamma}_{MNB}\hat{\sigma}^3_{MNB}\right), \tag{A6}$$

where $\hat{\sigma}_{MNB}$ is the weighted standard deviation in the distribution of benefits (again using α as the weights), and $\hat{\gamma}_{MNB}$ is the weighted skewness in this distribution. Here, we've made use of the definition of skewness:

$$\gamma_{MNB}\equiv\frac{E\left[MNB^3\right]-3E[MNB]\sigma^2_{MNB}-E[MNB]^3}{\sigma^3_{MNB}}.$$

Eq. (10) in the text follows using our sufficient condition that $\hat{\gamma}_{MNB}=0$.

Finally, consider a third order approximation of the change from the uniform policy to the state policy. In this case, $(MNB_i–p_i)=(MNB_i-\hat{\mu}_{MNB})$ and $dp_i=(MB_{ii}–\hat{\mu}_{MNB})$. Substituting these expressions into Eq. (A2), again using our assumption on the heterogeneity in the supply curves, and taking expectations yields:

$$dW\approx\frac{1}{2}N\frac{\partial G}{\partial p}\left(\hat{\sigma}_b^2-\hat{\mu}_s^2\right)+\frac{1}{6}N\frac{\partial^2 G}{\partial p^2}\left(\hat{\gamma}_b\hat{\sigma}_b^3+2\hat{\mu}_s^3\right), \tag{A7}$$

where $\hat{\sigma}_b$ is the weighted variance in within-state benefits and $\hat{\mu}_s$ is the weighted mean in spillovers. Eq. (11) follows from again setting $\hat{\gamma}_b=0$.

Proposition 1. The first part of Proposition 1, to the effect that the state policy approaches the first best as spillovers shrink to zero, follows immediately from Eq. (5). The second part of Proposition 1 follows from taking the derivative of Eq. (A7) with respect to $\hat{\mu}_s$. This is:

$$\frac{\partial(dW)}{\partial\hat{\mu}_s}\approx N\hat{\mu}_s\left(-\frac{\partial G}{\partial p}+\frac{\partial^2 G}{\partial p^2}\hat{\mu}_s\right)<0. \tag{A8}$$

Because $N\hat{\mu}_s$ is positive, for small $\hat{\mu}_s$, the sign of the term in parentheses is the same as the sign of $-\partial G/\partial p$, which is negative. Since the welfare loss under the state policy is monotonic in spillovers, this is true for all $\hat{\mu}_s$.[26]

[26] To see this, note that since $G(\,)$ is increasing we can write $dG\approx G'(-dp)+½G''(-dp)^2<0$ for all $dp>0$. Dividing by dp, we have $-G'+½G''dp<0$ for all dp. The proof then follows simply by setting $½dp=\hat{\mu}_s$.

Proposition 2. The first part of Proposition 2 similarly follows immediately from Eq. (10), while the second follows by taking the derivative of Eq. (A7) with respect to $\hat{\sigma}_b$. This is:

$$\frac{\partial(dW)}{\partial\hat{\sigma}_b}\approx N\left(\frac{\partial G}{\partial p}\hat{\sigma}_b+\frac{1}{2}\frac{\partial^2 G}{\partial p^2}\hat{\gamma}_b\hat{\sigma}_b^2\right)>0. \tag{A9}$$

Because $\partial G/\partial p$ is positive, this expression is clearly positive under our sufficient condition that the distribution of within-state benefits is symmetric, which completes the proof. Note, however, that this simplifying assumption is not needed. Dividing by $N\hat{\sigma}_b$, we have an expression of the form $G' + ½\, G''dp$, where $dp = \hat{\gamma}_b\hat{\sigma}_b$, which is positive for all dp since $G(\ )$ is an increasing function.

Proposition 3. To evaluate Proposition 3, note that as $MC(G)$ becomes more convex, G'' becomes smaller. Thus, the effect on the welfare difference of switching from the uniform to state policy, of a marginal increase in convexity, is $-\left(\hat{\gamma}_b\hat{\sigma}_b^3+2\hat{\mu}_s^3\right)$. Under our sufficient condition that γ_b is zero, this is negative, which completes the proof of the propositions.

More generally, the necessary condition is that

$$\gamma_b > -2\left(\frac{\hat{\mu}_s}{\hat{\sigma}_b}\right)^3.$$

This condition says that the skewness in within-state benefits cannot be too negative. The intuition is that if benefits are negatively skewed, the centralized policy will make its biggest mistakes by overpricing a few low-benefit jurisdictions. The second derivative will have its biggest impact in these outliers, so increasing convexity will accentuate the deadweight loss of the uniform policy as well. However, since benefits are non-negative, in most real-world applications they will probably be positively skewed, so this condition may generally be met in practice. (For example, the skewness in the distribution of air pollution benefits in our application is 1.8.)

Corollary

Finally, the corollary follows from setting the mean squared errors from the two policies equal: $\hat{\sigma}_b^2+\hat{\sigma}_s^2=\hat{\mu}_s^2+\hat{\sigma}_s^2$, or $\hat{\sigma}_b^2=\hat{\mu}_s^2$. In this case, expression (A7) collapses to:

$$dW\approx\frac{1}{6}N\frac{\partial^2 G}{\partial p^2}\left(\hat{\gamma}_b\hat{\sigma}_b^3+2\hat{\mu}_s^3\right).$$

When the marginal cost curves are linear, $\frac{\partial^2 G}{\partial p^2}=0$, and welfare under the two policies is identical. When they are convex, $\frac{\partial^2 G}{\partial p^2}$ is negative, and so switching from the centralized policy to the devolved policies decreases welfare under our sufficient condition of symmetric benefits (or the above necessary condition). When they are concave, $\frac{\partial^2 G}{\partial t^2}$ is positive, and switching from the centralized policy to the devolved policies increases welfare under the same conditions. This completes the proof of the corollary.

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