On the optimal allocation of regulatory power for public goods provision

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Abstract

In this paper, I develop a model of the regulatory game within and between different tiers of government to investigate the optimal allocation of regulatory power for public goods provision, and to examine circumstances under which partial devolution is the most efficient allocation of regulatory power. My results show that when local governments have better information about the local production technology than the central government does, a case for delegation via conjoint federalism can be made. Conjoint federalism is a common form of delegation in which the central government sets the standard and the local governments meet the standard. However, when the central government has an agency problem or when local governments have better information about local benefits or local costs, a case for delegation via reverse conjoint federalism can be made. Moreover, reverse conjoint federalism may be second-best when production functions are not injective and information problems are absent; if, in addition, either appropriate cost-sharing rules are implemented or output becomes contractible when the central government has power, reverse conjoint federalism can actually achieve the first-best outcome. My results have important implications for the issue of optimally distributing governmental power in the provision of public goods as well as for any problem of organizational choice in the presence of interjurisdictional externalities.

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1 Introduction

An important issue in the provision of public goods is how regulatory power should be distributed between central (or federal) and local (or state) tiers of government. Under what circumstances would it be optimal to distribute regulatory responsibility to both central and local tiers of government? In the context of the United States, for example, which regulatory decisions should be made by the federal government, and which by individual state governments? Likewise, in the context of the European Union, which regulatory decisions should be made by the European Commission, and which by individual member countries? In this paper, I develop a model of the regulatory game within and between different tiers of government to investigate the optimal allocation of regulatory power for public goods provision, and to examine circumstances under which partial devolution is the most efficient allocation of regulatory power.

In determining the optimal distribution of regulatory power between central and local governments, one should consider the tradeoffs involved in switching from complete centralization on the one hand to complete decentralization on the other. At one extreme, centralized, or federal, control has many advantages over decentralized, or local, public goods management, even when the federal government is constrained to treat all local districts uniformly.

The primary advantage of centralized control is that the central government can internalize any externalities that exist among local districts. Such an externality arises with transboundary pollutants, for example, because if the pollutant crosses state boundaries, then one state's pollution control efforts will affect another state's environmental quality. Under a decentralized system, the upwind (or upstream) state is less likely to account for the beneficial impact of its pollution control policy on its downwind (or downstream) neighbor than a central government under a centralized system would. Similarly, for educational public goods, one state's teaching training program may spill over to another state if teachers move from state to state, but under a decentralized system, individual states would not account for this positive externality when making their decisions about education policy. As long as the contractual environment were sufficiently incomplete to preclude individual states from coordinating via contracts and side payments, local control would yield the inefficient non-cooperative Nash equilibrium. The ability of federal control to internalize externalities and achieve a cooperative outcome is the main argument for centralization that I consider in this paper.[2]

When the federal government is able to treat local districts non-uniformly, as it will be allowed to do in my model, the case for centralization is strengthened further. If the choices of the local governments under decentralization are feasible under centralization, then centralization can achieve at least as much welfare as decentralization can.

Why, then, would one opt for the opposite extreme of completely decentralized management? In this paper, I consider two main arguments for decentralization. First, owing to agency problems, local governments may have preferences that are better aligned with local preferences than the federal government's preferences are and are therefore better able to tailor their policy to the preferences of their particular local constituents. As a consequence, while local governments act in the interest of citizen welfare, central governments do not.

[2]In addition to internalizing externalities, a second advantage of federal control is that it mitigates the "race to the bottom" that may ensue from decentralized decision-making and interjurisdictional competition. According to this line of argument, local control may lead to an underprovision of public goods because local officials would set excessively lax regulatory standards such as environmental standards in order to attract businesses to and create jobs in their respective districts (Oates, 2001). In contrast, under federal control such interjurisdictional competition would no longer occur. However, because economists have only recently begun to find empirical evidence that environmental regulations affect polluting industries' plant location, employment or investment decisions (see Levinson, 2003, & references therein), I do not include a possible race to the bottom in my model.

There are several other arguments for centralized control as well that I do not model. A third advantage of centralization is that manufacturers may prefer a uniform federal standard to heterogeneous local standards because the latter may require them to modify their product for each local market. Fourth, centralization may be justified on the basis of equity, for the federal government may be able to induce more equitable or redistributive outcomes than would otherwise arise from decentralized control. Fifth, the federal government may be the tier of government best suited for the gathering and dissemination of information about the benefits of the public good and on technologies and policies for producing the public good, and for the support and funding of research to generate such information. Sixth, if there are bureaucracy costs to increasing the number of tiers of government involved, costs analogous to those Qian (1994) studied in his model of hierarchies within firms, centralized control may be preferred to any system of partial decentralization in which both the federal and state levels of government play a role. I assume that all these considerations are secondary to the ability of a central government to coordinate decisions.

A second advantage of decentralization is that local governments may have better or more information about the local benefits from the public good, local costs of public goods provision, local technology, and/or any local conditions that may affect the effectiveness of policies to provide or produce public goods. Owing to this superior information, local governments are better suited for choosing the appropriate public goods provision policy. Thus, while the central government can better internalize externalities, local governments have better aligned preferences and more accurate local information.[3]

Because there are advantages and disadvantages to both centralized and decentralized systems of public goods provision, it is possible that some form of partial decentralization, in which the federal government has control but delegates some of its decisions to the local governments, may get the best of both worlds. This paper presents a model that captures the tradeoff between the ability of the federal government to internalize externalities and achieve coordination on the one hand and its failure to account for local preferences, costs, and production technology on the other. Such a model enables both a comparison of the extreme cases of federal control and local control with each other and with several forms of partial devolution, as well as a characterization of the optimal degree of decentralization.

I use this model to answer two main research questions. First, how does the second-best choice of power distribution vary with the extent of the externality, of differences in preferences, and of differences in information? Second, when is delegation the most efficient degree of decentralization and in what form should it take?

My results show that in some cases partial delegation can be preferred to both complete centralization and complete decentralization. Although I focus on public goods provision in

[3]There are several other arguments for decentralization that I do not consider in this paper. One is that local governments may have better or more information about local polluters, and, as a consequence, may be better able to monitor their activity than the federal government is. In this paper I assume that whichever tier of government has power has the ability to monitor local polluters, and that this ability is the same regardless of which tier has power. A second argument for decentralization that I do not consider is that imperfections in the decision making institutions at the federal level may dissipate some of the potential benefits of centralization. However, although I do not model these imperfections explicitly, I do capture their reduced-form implications that they lead the federal government to use an objective function and constraints that diverge from those that would be used by a social planner.

particular, the implications of my model are generalizable to any problem of organizational choice in the presence of interjurisdictional externalities.

The paper proceeds as follows. I review the previous literature in Section 2. I present the model in Section 3 and its results in Section 4. I examine the case for delegation when the production functions are not injective in Section 5. I apply my model to ozone smog regulation in Section 6. I conclude in Section 7.

2 Previous Literature

The main strand of literature relevant to this paper is that on federalism. According to Webster's dictionary (1991, p. 454), federalism is defined as "the distribution of power in an organization (as a government) between a central authority and the constituent units." In the context of the United States, and in the terminology used in this paper, the central authority is the federal government and the constituent units are the states. In the context of the European Union, the issue of federalism is sometimes termed "subsidiarity", which is "the principle whereby the Union does not take action (except in the areas which fall within its exclusive competence) unless it is more effective than action taken at national, regional or local level" (European Union, 2015b).

The issue of how to best distribute power between different tiers of government has been of interest to economists at least since the time Tiebout (1956), Musgrave (1959), Olson (1969), and Oates (1972) published their pioneering works on the topic. There is also a thriving literature on multi-jurisdictional environmental regulation (see e.g. Bui, 1998; Oates 2002; Sarnoff, 1997; List & Gerking, 2000; Sigman, 2005; Bulte, List & Strazicich, 2007; Ferrara, Missios & Yildiz, 2014; Fell & Kaffine, 2014; Andreen, 2016).

My work contributes to the federalism literature in several ways. First, it enables a comparison of some of the main competing arguments for local control. Most previous models of federalism focus exclusively on one of the disadvantages of centralization, whether it be inferior information about local conditions (Crémer, Estache & Seabright, 1996); diminished accountability to the wishes of any particular region or locality (Seabright, 1996); incentives that are not perfectly aligned with citizen welfare (see e.g. Qian & Weingast, 1997); an agency problem faced by the federal government (Alesina, Baqir & Hoxby, 2004; Lin, 2010b; Lin Lawell, 2017); a mismatch of local and federal incentives (Sjöberg, 2016); governance uncertainty (Aidt & Dutta, 2017); or imperfections in the decision making institutions at the federal level such as an inability to treat local districts non-uniformly (see e.g. Oates, 1972), restrictions on voting and/or cost-sharing rules (see e.g. Besley & Coate, 2003; Crémer and Palfrey, 2006; Hafer and Landa, 2007; Loeper, 2013), legislative rules (Lockwood, 2002), or the need to use the same rules for different projects (Rubinchik-Pessach, 2005). Although the mechanisms underpinning these disadvantages are different, their reduced-form implications are the same: the federal government does not maximize social welfare because its objective function and constraints differ from those that would be used by a benevolent social planner. By positing that the federal government uses benefit, cost, and production functions in its optimization problem that are potentially different from the ones a benevolent social planner would use, while remaining agnostic about the actual source of the dichotomy, I am able to at least partially capture these erstwhile separate arguments for decentralization in a single meta-model.

A second contribution this paper makes to the federalism literature is that it develops a theory for partial devolution. The majority of models in the federalism literature consider only the extremes of complete centralization and complete decentralization; in contrast, my model allows for intermediate forms of decentralization as well.

3 Model

3.1 Regulatory Decisions

A common form of public goods regulation involves the setting and meeting of standards for a particular public good in question. This good, which I term "output", is the good regulators care about and can represent, for example, renewable energy production, local air quality, or student achievement. Let q_i denote the "output" in state i.

In order to produce the output public good, policies must be implemented. I call these policies "inputs". The input policy of each state i is given by a_i. Different values of the input policy a_i can represent different input policies, different levels or intensities of the same input policy, and/or different combinations of policies, ordered from lowest to highest cost.

There are many reasons why input policies may spill over from one state to another. First, if input policies were implemented to generate and disseminate knowledge and other forms of human capital, then such human capital could easily spill over to other states. An example of such a knowledge spillover are research and development spillovers. Second, if input policies were aimed at regulating a mobile factor, then the effects of these policies would spill over whenever that mobile factor moved across state boundaries. For example, if input policies were implemented to train teachers, then the effects of these policies would spill over to other states whenever the teachers moved from state to state. Similarly, if input policies were implemented to abate emissions from cars and trucks, then the effects of these policies would spill over whenever these vehicles were driven in other states. A third reason input policies may spill over is that certain choices of these input policies may lead to spillovers to other states. For example, some state governments free ride on their neighbors by allowing plants located near state borders to emit more pollution than plants that are not located near state borders (Sigman, 2005; Helland & Whitford, 2003; Gray and Shadbegian, 2004; Gray and Shadbegian, 2008).

I model regulation as a two-stage process. In the first stage, the output q_i is chosen for each state i. In the second stage, the input policy a_i is chosen for each state i in order to implement the output vector (q_1, q_2) chosen in the first stage.[4] I assume that, irrespective of who makes the choice, input policies are always chosen to meet the output dictated in stage 1 with equality. Output q_i can thus be interpreted as a standard that state i must attain.[5] There are thus two types of decisions that can be made for each state i: decisions about output q_i and decisions about the conditional input policy a_i, where by "conditional input" I mean input conditional on output.

3.2 Decentralization Scenarios

In my model, governmental power encompasses the right to make decisions and the ability to enforce them. There are two types of power: one for each of the two stages of regulation. **Output power** is the right and ability to set, measure, monitor, and enforce the standard for output q_i in stage one. **Input power** is the right and ability to choose, measure, monitor, and enforce the (conditional) input policy a_i to meet the standard in stage two.[6]

The two types of power can be separately allocated to different tiers of government. As shown in Table 1, each decentralization scenario that I consider corresponds to a different allocation of power between the federal tier of government and the state tier of government.

To achieve the social optimum, a social planner would have the power to choose both the output standard and the conditional input policy for each state. In other words, the social planner would have both output power and input power over both states. The solution to

[4] I choose this particular sequential setup for two main reasons. First, if, instead, the input policy levels were chosen first, then the output levels would already be determined and therefore could no longer be chosen independently. In order to distinguish output power from input power, I therefore model the output level as being chosen first. Second, the sequential nature of my regulatory model accords well with many actual forms of regulation in which one regulatory body sets a standard (or output target) that another agency must attain.

[5] In the United States, if states fail to meet air quality standards, federal highway funds may be withheld (John List, personal communication, September 3, 2003).

[6] I sometimes refer to the stage-two input policy choice as a "conditional" input policy choice, since the choice is conditional on the stage-one output standard.

Table 1: The Allocation of Power

Decentralization Scenario	Output Power	Input Power
Social Optimum	P	P
State Control	S	S
Federal Control	F	F
Conjoint Federalism	F	S
Reverse Conjoint Federalism	S	F

Notes: The distribution of the two types of power under the different decentralization scenarios. P denotes the social planner, F denotes the federal government, and S denotes the state governments.

her problem yields the socially efficient choice of output and input policies, since it accounts for both local preferences and local information as well as cross-state externalities. It is against this first-best benchmark that I will compare various scenarios of decentralization.

Complete decentralization corresponds to **state (S) control**, in which each state has the power to choose both its own output standard and its own conditional input policy. Thus, each state retains its own output power and input power. In the noncooperative Nash equilibrium that ensues, each state's choice is a best response to the other state's choice.

In the opposite extreme, complete centralization corresponds to **federal (F) control**, in which the federal government has the power to choose both the output standard and the conditional input policies for all states. The federal government thus has both output power and input power over both states. Federal control is similar to social planner control because both scenarios involve allocating all power to one centralized authority; federal control differs from social planner control, however, because the federal government uses benefit, cost, and production functions that may differ from those of the social planner.

When externalities exist and when the federal government's preferences diverge from social welfare, neither state control nor federal control achieves the social optimum. As a consequence, it is possible that the most efficient regulatory structure may involve delegation: the central government retains the power to either set or meet the standard, but not both, and delegates the power to make the remaining decision to the local governments.

In this paper I examine two forms of delegation. The first form of delegation is **conjoint federalism (C)**, in which the federal government retains the power to set the output standards for both states but delegates to each state the power to decide its own conditional input policies to meet the standard. Thus, the federal government has output power but each state has its own input power. This form of delegation is the one currently used in both the United States and the European Union for air quality regulation: the federal government sets ambient air quality standards that each state must implement policies to meet (Farrell & Keating 1998; European Union, 2015a).[7] Beginning in 1969, conjoint federalism supplanted state control for many environmental regulations in the United States as a result of federal research in pollution, mounting public concern with environmental issues and the ineffectiveness of state pollution control efforts. Because conjoint federalism is inflexible and constrains state autonomy, however, states backlashed against it in the early 1990s (Keleman, 2004).

The second form of delegation is **reverse conjoint federalism (R)**, in which the federal government commits to delegating to each state the power to choose its own output level while retaining for itself the power to choose both states' conditional input policies. Thus, the federal government has input power while the states each have their own output power.

Although reverse conjoint federalism less common, some regulatory structures do resemble this form. In the context of renewable energy regulation in the United States, the federal government aids states in meeting the renewable portfolio standards (or "output standards") they each set on their own via incentives for research and development in renewable energy (as an "input policy"). For the regulation of crime in the United States, the federal government aids the states in meeting the criminal laws (or "output standards") they each set on their own by providing (as an "input policy") the Federal Bureau of Investigation's fingerprint service. Similarly, while states set individual child support laws (output), the

[7]Indeed, the term "conjoint federalism" was used by Farrell and Keating (1998) to describe the U.S. ozone regulatory structure. I use this term from their paper.

United States federal government implements (input) policies to address, enforce and collect interstate child support payments when parents live in different states. Reverse conjoint federalism also appears to describe the underlying philosophy of the World Trade Organization (WTO). For example, Article 20 of the GATT allows member countries to each set their own health and safety standards, but the WTO sets the code of practice (the "input policy") for preparing, adopting and applying these standards. Similarly, member countries can each decide their own trade policies and practices (output), while the WTO is responsible for reviewing and meeting these policies (input).

3.3 Benefits, Costs, and Production Technology

In my simple model, there is one federal government and two state governments.[8] The aggregate benefit to residents of state i of output q_i is $V_i(q_i)$. I remain agnostic about how individual public goods benefits are aggregated to the state level. Benefits are measured in terms of money equivalents. Because I use the sum over all states of the aggregate benefits to each state i as my welfare criterion, I call $V_i(q_i)$ the "true" benefit function for state i.

While each state government uses its correct respective aggregate benefit function in assessing the benefits of the output good, the federal government does not. For each state i, the federal government uses the "federal" benefit function $V_{F,i}(q_i)$ as the aggregate state benefit instead of the "true" benefit function $V_i(q_i)$. Both $V_i(\cdot)$ and $V_{F,i}(\cdot)$ are nondecreasing, concave, and differentiable.

There are many possible reasons why the benefit functions used by the federal government may not reflect the true benefit functions.[9] First, voting rules might create a divergence between federal and local preferences. For example, if preferences of governments reflect those of the median voter among their constituents, and if states were heterogeneous,[10] then

[8] My model can of course be generalized to any organization consisting of a central authority and constituent units.

[9] I assume in this paper that the preferences of the state governments are perfectly aligned with local welfare. The same arguments still apply even if this assumption were relaxed, as long as the preferences of the state governments are better aligned with local preferences than those of the federal government are.

[10] Carruthers and Lamoreaux (2016) find that it is common for political pressures within jurisdictions to

the median voter in the entire nation would not be the same as the median voter in each state. Since their median voters would differ, state and federal governments would have different preferences. Voting institutions such as the electoral college system may also create incentives for the federal government to care about some states more than others.

A second reason why the federal government may fail to maximize social welfare is that, for equity reasons, it may prefer to use the same benefit function for all states, even if the states are heterogeneous. For example, it may be constrained, perhaps by legislation, to value education or the environment in both states equally.

A third source of an agency problem is the need for the federal government to balance domestic with foreign policy objectives. Owing to possible trade-offs between national and international interests, the federal government may not be able to fully attend to domestic concerns.

A fourth reason why the federal government might not use the true benefit functions is an information problem: the federal government is unable to correctly measure what the true benefits are, as such information may be local or private information to the states, and therefore uses an incorrect estimate of them.

Thus, voting rules, equity concerns, international objectives, and informational asymmetries are all potential reasons why the the benefit functions used by the federal government may not reflect the true beneift functions. As the model in this paper is agnostic about the actual mechanism underlying the agency and information problems, my results do not hinge on the verity of any particular agency or information story, but rest only on the assumption that *some* story exists that makes the state government's preferences better aligned with local welfare than the federal government's preferences are. Thus, the model is general enough to capture the reduced-form implications of any of a number of agency or information stories.

There are costs to implementing the input policy a_i chosen to produce the output public good q_i. For each state i, implementing input policy a_i imposes a cost $C_i(a_i)$. While each

produce a heterogeneous pattern resembling Tiebout sorting.

state government uses its correct respective cost function in assessing the costs of input, the federal government does not. For each state i, the federal government's estimate of state i's cost function is given by the "federal" cost function $C_{F,i}(a_i)$. Both $C_i(\cdot)$ and $C_{F,i}(\cdot)$ are nondecreasing, convex, and differentiable.

Owing to externalities in input policies, each state i's public good output is the following function of both its own input policy and the input policy of the other state j:

$$q_i = f_i(a_i + \alpha_i a_j), \tag{1}$$

where $f_i(\cdot)$ reflects state i's technology of translating input into output, where $\alpha_i \in [-1, 1]$ measures the extent of the externality, and where $A_i \equiv a_i + \alpha_i a_j$ is the effective input in state i. I assume that the externalities $\{\alpha_i\}_{i=1,2}$ are known to all governments. Thus, while each state only incurs the cost of its own input, its benefits depends on the input policies of both states through their effect on that state's own output.

It is possible for the production function $f_i(\cdot)$ to be a multi-valued correspondence. In other words, it is possible that there are multiple values of the effective input A_i that yield a given output q_i. Thus, it is possible for there to be multiple possibilities for the input policy choice in stage two that would achieve a given output choice from stage one. It is therefore possible that the conditional input policies chosen in a non-cooperative Nash equilibrium to implement any given vector of output choices $q = (q_i, q_j)$ may differ from the socially optimal conditional input chocies that would be chosen in the social optimum.

Since the federal government may not know the true production technology $f_i(\cdot)$, its assessment of state i's technology is instead given by $f_{F,i}(\cdot)$.

The utility U^i for each state i is simply the benefits it accrues from the output good minus the costs it incurs to achieve it:

$$U^i = V_i(q_i) - C_i(a_i). \tag{2}$$

Thus, while each state only incurs the cost of its own input, its benefits depends on the input policies of both states through their effect on that state's own output. I assume that each state i will always act so as to maximize its own utility U^i.

Since each state government's utility function correctly reflects the aggregate utility of its citizens, total welfare W is given by the sum of the utilities of all the states:

$$W = \sum_i U^i = \sum_i \left[V_i(q_i) - C_i(a) \right]. \tag{3}$$

A social planner would use total welfare W as her objective function.

In contrast, because the federal government uses its own benefit function and cost function in place of the true benefit function and true cost function, respectively, the federal government's objective function U^F is given by:

$$U^F = \sum_i [V_{F,i}(q_i) - C_{F,i}(a_i)]. \tag{4}$$

I assume that the federal government will always act so as to maximize U^F, even though the benefits of output and the costs of input accrue to the citizens of the individual states.

3.4 Social Optimum

The social optimum would arise if a social planner had both input power and output power. In order to establish the first-best benchmark against which I will compare the various decentralization scenarios, I first derive the solution to the social planner's problem.

The social planner's two-stage regulatory problem is solved backwards. In the second stage of regulation, the social planner chooses the input policy a_i for each state i in order to meet the output levels $q = (q_1, q_2)$ chosen in stage one. Given the output levels $q = (q_1, q_2)$ chosen in stage one, the input policy a_i for each state i must satisfy the following system of constraints:

$$\begin{aligned} A_i &\in f_i^{-1}(q_i) \ \forall i \qquad (5) \\ A_i &\equiv a_i + \alpha_i a_j \ \forall i, j \neq i \ , \qquad (6) \end{aligned}$$

where, for each state i, the inverse $f_i^{-1}(\cdot)$ of the production function is a correspondence.

Solving the system of contraints in equations (5) and (6) for input, we obtain that, as a function of the output levels $q = (q_1, q_2)$ chosen in stage one, the input policies $a_i(q)$ for each state i must satisfy:

$$a_i(q) \in \left\{ \frac{1}{1 - \alpha_i \alpha_j} (A_i - \alpha_i A_j) \mid A_i \in f_i^{-1}(q_i), \ A_j \in f_j^{-1}(q_j) \right\} \ \forall i, j \neq i \ . \qquad (7)$$

If for both states the inverse of the production function were a single-valued function instead of a multi-valued correspondence (i.e., if both production functions were injective), then the input policies would be given by:

$$a_i(q) = \frac{1}{1 - \alpha_i \alpha_j} \left(f_i^{-1}(q_i) - \alpha_i f_j^{-1}(q_j) \right) \ \forall i, j \neq i \ . \qquad (8)$$

Because the social planner has input power over all states, the conditional input policies will be chosen cooperatively. In particular, given any vector of outputs, she would choose input so as to minimize the sum of the costs to the two states. I will call conditional input policies *cost-effective* if, among all input policies that achieve a given target of output vectors $q = (q_i, q_j)$, they implement the given output vector at minimum total cost. The cost-effective input choice by the social planner is given by:

$$\left(a_i^P(q), a_j^P(q)\right) = \underset{(a_i,a_j)}{\arg\min} \left[C_i(a_i) + C_j(a_j) \mid a_i = \frac{1}{1-\alpha_i\alpha_j}(A_i - \alpha_i A_j),\ A_i \in f_i^{-1}(q_i)\ \forall i, j \neq i \right]. \quad (9)$$

In the first stage of regulation, the social planner chooses the output levels $q = (q_1, q_2)$. Substituting in equation (9) for the cost-effective input vector $\left(a_i^P(q), a_j^P(q)\right)$, the social planner's first-stage output choice problem is given by:

$$\left(q_i^P, q_j^P\right) = \underset{\{q_i\}_i}{\arg\max} \left(\sum_i V_i(q_i) - C_i(a_i^P(q)) + C_j(a_j^P(q)) \right) . \quad (10)$$

The solution to equation (10) yields the socially efficient output vector $q^P = (q_i^P, q_j^P)$; plugging the socially efficient output vector $q^P = (q_i^P, q_j^P)$ into equation (9) for the cost-effective input vector $\left(a_i^P(q), a_j^P(q)\right)$ yields the socially efficient input vector $a^P = (a_i^P, a_j^P)$.

If for both states the inverse of the production function were a single-valued function instead of a multi-valued correspondence (i.e., if both production functions were injective), then the first-order condition for the output levels would be given by:

$$V_i'(q_i) = \frac{C_i'(a_i) - \alpha_j C_j'(a_j)}{f_i'(a_i + \alpha_i a_j) \cdot (1 - \alpha_i \alpha_j)} \forall i, j \neq i \ . \quad (11)$$

This first-order condition can be interpreted as setting the marginal social benefits of output to the marginal social costs of the input needed to achieve that output.[11]

The social planner's solution accounts for both local conditions (i.e., preferences, costs and production technology) as well as the cross-state externalities. It is against this first-best benchmark that we will compare various scenarios of decentralization.

[11] The second-order conditions would be automatically satisfied if the set $\{(a_i, a_j, q_i, q_j) | q_i = f_i(a_i + \alpha_i a_j) \forall i, j \neq i\}$ were convex. This is because the first-order conditions from a problem of maximizing a concave function over a convex set are both necessary and sufficient for characterizing a global solution.

3.5 State Control

Under state control, each state retains its own input power and output power, and both inputs and outputs are chosen non-cooperatively. In the second stage of regulation, a Nash equilibrium in inputs would arise in which, for any given vector of outputs, each state would choose the conditional input policies that minimize its own costs of implementing its target output subject to the input policies chosen by the other state. Solving the constraint for input as a function of output yields, for each state i:

$$a_i \in \left\{ A_i - \alpha_i a_j \mid A_i \in f_i^{-1}(q_i) \right\} . \tag{12}$$

Given its own output q_i and the other state's input a_j, state i chooses, among all input policies that achieve the given output, the input policy a_i that minimizes input costs. Since input costs are nondecreasing (i.e., $C_i'(a_i) \geq 0$), then this means that the state chooses the lowest input among all input policies that achieve the desired output. In other words, for each state i, input choice conditional on output is given by the following reaction function:

$$a_i = \min \left\{ A_i \mid A_i \in f_i^{-1}(q_i) \right\} - \alpha_i a_j. \tag{13}$$

The non-cooperative Nash equilibrium input policies that result are thus given by:

$$a_i^S(q) = \frac{1}{1 - \alpha_i \alpha_j} \left(\min \left\{ A_i \mid A_i \in f_i^{-1}(q_i) \right\} - \alpha_i \min \left\{ A_j \mid A_j \in f_j^{-1}(q_j) \right\} \right) \forall i, j \neq i \ . \tag{14}$$

Note that, for any vector of output levels to be implemented, the Nash equilibrium input policies $a_i^S(q)$ given by equation (14) are not necessarily the same as the socially efficient input policies $a_i^P(q)$ given by equation (9). However, if for both states the inverse of the production function were a single-valued function instead of a multi-valued correspondence (i.e., if both production functions were injective), then the Nash equilibrium input policies

$a_i^S(q)$ would be the same as the socially efficient input policies $a_i^P(q)$, since there would be a unique set of input policies $a = (a_i, a_j)$ that implements any given vector of output levels $q = (q_i, q_j)$.

Substituting in its second-stage reaction function (14) for input $a_i^S(q)$, each state i's first-stage output choice problem reduces to:

$$q_i^S = \arg\max_{q_i} V_i(q_i) - C_i(a_i^S(q)) \ . \tag{15}$$

The solution to equation (15) yields the output level q_i^S that solves each state i's problem; substituting q_i^S into equation (14) for $a_i^S(q)$ yields each state's choice of input a_i^S.

If the second-stage reaction function (14) for input $a_i^S(q)$ were differentiable with respect to output, then the output choice would be given by:

$$V_i'(q_i) = \frac{C_i'(a_i)}{1-\alpha_i\alpha_j} \cdot \frac{\partial}{\partial q_i} \min\left\{A_i \mid A_i \in f_i^{-1}(q_i)\right\} \ . \tag{16}$$

If the production functions were injective, then the first-order condition for output would be given by:

$$V_i'(q_i) = \frac{C_i'(a_i)}{f_i'(a_i + \alpha_i a_j) \cdot (1-\alpha_i\alpha_j)}. \tag{17}$$

This first-order condition can be interpreted as setting the marginal private benefits of output to the marginal private costs of the input needed to achieve that output.

Under state control, both the input policies and the output standards are chosen non-cooperatively. As a consequence, states fail to internalize externalities in both stages of the regulatory process.

3.6 Federal Control

Under federal control, the federal government has input power and output power over all states.

In the second stage of regulation, the federal government chooses the input policy a_i for each state i in order to meet the output levels $q = (q_1, q_2)$ chosen in stage one. Given the output levels $q = (q_1, q_2)$ chosen in stage one, the input policy a_i for each state i must satisfy the following:

$$a_i(q) \in \left\{ \frac{1}{1-\alpha_i\alpha_j}(A_i - \alpha_i A_j) \mid A_i \in f_{F,i}^{-1}(q_i),\ A_j \in f_{F,j}^{-1}(q_j) \right\} \forall i, j \neq i \ , \tag{18}$$

where, for each state i, the inverse $f_{F,i}^{-1}(\cdot)$ of the federal government's assessment of the production function is a correspondence.

If for both states the inverse of the assessed production function were a single-valued function instead of a multi-valued correspondence, then the input policies would be given by:

$$a_i(q) = \frac{1}{1-\alpha_i\alpha_j}(f_{F,i}^{-1}(q_i) - \alpha_i f_{F,j}^{-1}(q_j)) \forall i, j \neq i. \tag{19}$$

Given any vector $q = (q_i, q_j)$ of outputs, the federal government would choose the vector of input policies to minimize its assessment of total costs. That is,

$$\begin{aligned} &\left(a_i^F(q), a_j^F(q)\right) = \\ &\quad \arg\min_{(a_i, a_j)} \left\{ C_{F,i}(a_i) + C_{F,j}(a_j) \mid a_i = \frac{1}{1-\alpha_i\alpha_j}(A_i - \alpha_i A_j),\ A_i \in f_{F,i}^{-1}(q_i) \forall i, j \neq i \right\} \ . \end{aligned} \tag{20}$$

Note that if the federal government incorrectly assesses local costs and/or local production technology, then equation (20) for input $a_i^F(q)$ is different from equation (9) for input $a_i^P(q)$ arising in the social optimum.

The federal government's first-stage output choice problem is given by:

$$\left(q_i^{F,d}, q_j^{F,d}\right) = \underset{\{q_i\}_i}{\arg\max} \left(\sum_i V_{F,i}(q_i) - C_{F,i}(a_i^F(q)) + C_{F,j}(a_j^F(q))\right) . \tag{21}$$

If the assessed production functions $f_{F,i}(\cdot)$ were injective for both states i, then the solution to the federal government's first-stage output choice problem (21) would be characterized by the following first-order condition:

$$V'_{F,i}(q_i) = \frac{C'_{F,i}(a_i) - \alpha_j C'_{F,j}(a_j)}{f'_{F,i}(a_i + \alpha_i a_j) \cdot (1 - \alpha_i \alpha_j)} \forall i, j \neq i. \tag{22}$$

The solution to the federal government's first-stage output choice problem (21) yields the desired output levels $q^{F,d}$ that arise under federal control; substituting the desired output levels $q^{F,d}$ into equation (20) for input $a_i^F(q)$ yields the federal government's choice of input policy a^F. The federal government's desired solution is therefore given by $(a^F, q^{F,d})$.

Because the federal government incorrectly assesses local technology, the realized output level $q_i^{F,r}$ that arises for each state i based on its input choice is not its desired output $q_i^{F,r}$ but is instead given by the output produced when the actual production technology is applied to the federal government's choice of input $a^F \equiv \left(a_i^F(q^{F,d}), a_j^F(q^{F,d})\right)$:

$$q_i^{F,r} = f_i(a_i^F(q^{F,d}) + \alpha_i a_j^F(q^{F,d})) . \tag{23}$$

Thus, under complete centralization, the input and output levels that are realized are $(a^F, q^{F,r})$. The federal government accounts for externalities but not for local benefits, costs, or production technology. In particular, if the federal government's functions for benefits, costs and technology were all correct, then complete centralization would achieve the first best since the equations characterizing $(a^F, q^{F,r})$ would be equivalent to those characterizing (a^P, q^P).

3.7 Conjoint Federalism

When externalities exist and when the federal government's assessments of local conditions diverge from the truth,[12] neither state control nor federal control achieves the social optimum. As a consequence, it is possible that a form of partial decentralization, or delegation, may be more efficient that either extremes of decentralization. In one form of delegation, the federal government chooses output first and then delegates the input choice to the respective states.[13] This form of delegation is sometimes termed conjoint federalism (Farrell & Keating, 1998) and is the particular form currently used in the United States for ozone smog regulation.

Under conjoint federalism, the state governments have input power while the federal government has output power. In the second stage of regulation, a Nash equilibrium in inputs would arise in which, for any given vector of outputs, each state would choose the input policy that minimize its own costs of implementing its target output subject to the input policy chosen by the other state. The states would solve the same second-stage problem under conjoint federalism as they would solve under state control. The conditional input choices $a_i^C(q)$ under conjoint federalism are therefore the same as the input policies $a_i^S(q)$ under state control given by equation (14). In other words:

$$a_i^C(q) = a_i^S(q) = \frac{1}{1-\alpha_i\alpha_j}\left(\min\left\{A_i \mid A_i \in f_i^{-1}(q_i)\right\} - \alpha_i \min\left\{A_j \mid A_j \in f_j^{-1}(q_j)\right\}\right) \forall i, j \neq i \ . \quad (24)$$

Thus, just as under state control, the conditional input choices under conjoint federalism are not cost effective.

[12] I use the term "assessment"loosely throughout this paper. If the federal government's "assessment"of benefits diverges from the truth, this divergence might reflect either differing preferences or inferior information. Unless otherwise specified, my notion of "assessment"encompasses both preferences and information.

[13] If the states were to choose the input policies first, then the output levels would already be determined and therefore could no longer be chosen independently. The form of delegation in which state governments choose their input policies first before the federal government chooses the output levels is therefore equivalent to complete decentralization. Thus, it need not be separately analyzed.

However, because the federal government incorrectly assessed the production technology, it thinks that the Nash equilibirum input policies are instead given by:

$$a_i^{C,b}(q) = \frac{1}{1-\alpha_i\alpha_j}\left(\min\left\{A_i \mid A_i \in f_{F,i}^{-1}(q_i)\right\} - \alpha_i \min\left\{A_j \mid A_j \in f_{F,j}^{-1}(q_j)\right\}\right) \;\forall i, j \neq i \;. \quad (25)$$

In stage one of the game, the federal government would choose outputs in a coordinated fashion, while anticipating a non-cooperative conditional input choice by the states in stage two. In particular, the federal government chooses the output levels to maximize its utility subject to its beliefs $a_i^{C,b}(q)$ of the states' functions for input condition on output. Its problem is thus given by:

$$\left(q_i^C, q_j^C\right) = \arg\max_{\{q_i\}_i} \left(\sum_i V_{F,i}(q_i) - C_{F,i}(a_i^{C,b}(q)) + C_{F,j}(a_j^{C,b}(q))\right) . \quad (26)$$

If the federal government's assessment $f_{F,i}(\cdot)$ of the production function were injective for each state i, then the first-order conditions would be given by:

$$V'_{F,i}(q_i) = \frac{C'_{F,i}(a_i) - \alpha_j C'_{F,j}(a_j)}{f'_{F,i}(a_i + \alpha_i a_j)\cdot(1-\alpha_i\alpha_j)} \forall i, j \neq i \;. \quad (27)$$

Thus, under conjoint federalism, the federal government's choice of output q^C is given by equation (26) while each states' actual choice of input $a^C(q)$ conditional on output is given by equation (24).

3.8 Reverse Conjoint Federalism

Under reverse conjoint federalism, the federal government has input power while the state governments have output power. In the second stage of regulation, the federal government chooses conditional input policies in a coordinated fashion to minimize its assessment of total costs, subject to its beliefs about the production technology. The federal government would therefore solve the same second-stage problem under reverse conjoint federalism as it would solve under federal control. The conditional input choices $a_i^R(q)$ under reverse conjoint federalism are therefore given by equation (20) for input $a_i^F(q)$ under federal contol In other words:

$$\left(a_i^R(q), a_j^R(q)\right) = \left(a_i^F(q), a_j^F(q)\right) =$$
$$\arg\min_{(a_i,a_j)} \left\{ C_{F,i}(a_i) + C_{F,j}(a_j) \mid a_i = \frac{1}{1-\alpha_i\alpha_j}(A_i - \alpha_i A_j),\ A_i \in f_{F,i}^{-1}(q_i) \forall i, j \neq i \right\} \ . \quad (28)$$

I assume that each state knows that the federal government bases its decision on its assessed cost and production functions, and that each state knows what the federal government's assessed cost and production functions are. Each state then solves the following problem in the first stage of reverse conjoint federalism:

$$q_i^S = \arg\max_{q_i} V_i(q_i) - C_i(a_i^R(q)) \ . \quad (29)$$

If the production function were injective, the first-order condition would be given by:

$$V_i'(q_i) = \frac{C_i'(a_i)}{f_{F,i}'(a_i + \alpha_i a_j) \cdot (1 - \alpha_i\alpha_j)} \forall i, j \neq i \ . \quad (30)$$

4 Results

4.1 Achieving the first best

Let W^P, W^S, W^F, W^C, and W^R denote the social welfare achieved under the social planner, state control, federal control, conjoint federalism, and reverse conjoint federalism, respectively. The following results establish when the first-best welfare level can be achieved. I start with three Lemmas that accord well with general intuition.

Lemma 1 *If there are no externalities and if the federal government correctly accounts for all local conditions, then all decentralization scenarios are first-best efficient (i.e.,* $W^S = W^F = W^C = W^R = W^P$*).*

Proof. *If,* $\forall i$*,* $\alpha_i = 0$*,* $V_{F,i}(\cdot) = V_i(\cdot)$*,* $C_{F,i}(\cdot) = C_i(\cdot)$*, and* $f_{F,i}(\cdot) = f_i(\cdot)$*, then, for each decentralization scenario, the equations characterizing the solution arising under that scenario become equivalent to the those characterizing the solution under the social planner. For all scenarios, the input choice would be given by:*

$$a_i^*(q) = \arg\min_{a_i} \left[C_i(a_i) \mid a_i \in f_i^{-1}(q_i)\right] \;\; \forall i, \tag{31}$$

and the output level would be given by:

$$q_i^* = \arg\max_{q_i} \; V_i(q_i) - C_i(a_i^*(q)) \; \forall i. \tag{32}$$

If the production function were injective for each state, then the first order condition would be given by:

$$V_i'(q_i) = \frac{C_i'(a_i)}{f_i'(a_i)} \; \forall i. \tag{33}$$

■

That is, when there are no problems of coordination, agency, or information, then there are no sources of inefficiency at either extreme of decentralization. As a consequence, both extremes are efficient, as are all intermediate forms of partial decentralization in between as well.

Lemma 2 *State control achieves the first best (i.e.,* $W^S = W^P$*) when there are no externalities (i.e.,* $\alpha_i = \alpha_j = 0$*).*

Proof. *If $\alpha_i = \alpha_j = 0$, then, because $C_i'(a_i) \geq 0 \ \forall i$, the Nash equilibrium input policies $a_i^S(q)$ from equation (14) chosen to implement any given output vector are equivalent to the cost-effective input policies $a_i^P(q)$ from equation (9); both are given by:*

$$a_i^*(q) = \min \left\{ A_i \mid A_i \in f_i^{-1}(q_i) \right\} \ \forall i \ .$$

Since the welfare of each state no longer depends on the choices of the other state, maximizing total welfare becomes equivalent to maximing each state's welfare separately. Thus, in both the social planner's problem and the state's problem, state i's output is given by equation (15). ■

Intuitively, state control is efficient in the absence of spillovers because if one state's choices has no effect on the other, then no inefficiencies arise from letting the states choose their own input and output.

Lemma 3 *Federal control achieves the first best (i.e., $W^F = W^P$) when the federal government correctly accounts for all local conditions (i.e, $V_{F,i}(\cdot) = V_i(\cdot)$, $C_{F,i}(\cdot) = C_i(\cdot)$, and $f_{F,i}(\cdot) = f_i(\cdot) \ \forall i$).*

Proof. *If $f_{F,i}(\cdot) = f_i(\cdot) \ \forall i$, then the federal government's desired output level will be realized under federal control, since the inputs $a_i^F(q)$ chosen based on equation (20) to meet the desired output levels q^F will produce the desired output in actuality. Thus, the desired solution $(a^F, q^{F,d})$ characterized by equations (20) and (21) is also the realized solution $(a^F, q^{F,r})$ under federal control. Further, if, in addition, , $V_{F,i}(\cdot) = V_i(\cdot)$ and $C_{F,i}(\cdot) = C_i(\cdot) \ \forall i$, then the two equations (20) and (21) characterizing the desired input choice and output levels under federal control become equivalent to the two equations (9) and (10) that characterize the socially optimal input and output levels. Since the desired input choice and output levels are achieved, the realized solution under federal control is first best.* ■

Thus, if the federal government correctly accounts for all local conditions – i.e, if there are neither agency nor information problems – then complete centralization will implement the first best.

I now proceed to results which establish when partial devolution is socially efficient.

Proposition 4 *Conjoint federalism achieves the first best (i.e.,* $W^C = W^P$*) if the federal government correctly accounts for all local conditions (i.e.,* $V_{F,i}(\cdot) = V_i(\cdot)$, $C_{F,i}(\cdot) = C_i(\cdot)$*, and* $f_{F,i}(\cdot) = f_i(\cdot)\ \forall i$*) and if either the production functions* $f_i(\cdot)$ *are injective* $\forall i$ *or externalities are absent (i.e.,* $\alpha_i = \alpha_j = 0$*).*

Proof. *If,* $\forall i$, $f_{F,i}(\cdot) = f_i(\cdot)$ *and either* $f_i(\cdot)$ *is one-to-one or* $\alpha_i = \alpha_j = 0$*, then the Nash equilibrium input policies* $a_i^C(q)$ *in equation (24) chosen to implement any given output vector are equivalent to the cost-effective input policies* $a_c^P(q)$ *given by equation (9). If, in addition,* $V_{F,i}(\cdot) = V_i(\cdot)$ *and* $C_{F,i}(\cdot) = C_i(\cdot)\ \forall i$*, then the first-stage maximization problem (21) of the federal government under conjoint federalism becomes equivalent to the first-stage maximization problem (9) of the social planner.* ■

The intuition is the following. When either the production functions are injective or externalities are non-existent, states always make the cost-effective choice of input needed to implement any given output, since only one pair of input policies can correctly implement any given vector of ouput levels. Moreover, when it correctly accounts for all local conditions, the federal government always makes the most efficient choice for output given the states' reaction functions for input given output. Since the reaction functions are first-best efficient, both output and input are first-best efficient.

Proposition 5 *Reverse conjoint federalism achieves the first best (i.e.,* $W^R = W^P$*) when* *there are neither externalities (i.e., $\alpha_i = \alpha_j = 0$) nor errors in the federal government's assessment of local production technology (i.e., $f_{F,i}(\cdot) = f_i(\cdot)\ \forall i$).*

Proof. *If $f_{F,i}(\cdot) = f_i(\cdot)\ \forall i$ and $\alpha_i = \alpha_j = 0$, then because $\forall i$, $C_i'(a_i) \geq 0$ and $C_{F,i}'(a_i) \geq 0$, the input policies chosen by the federal government are equivalent to those that would be chosen by the social planner, namely:*

$$a_i^*(q) = \min\left\{A_i \mid A_i \in f_i^{-1}(q_i)\right\}\ \forall i\ . \tag{34}$$

Since the welfare of each state no longer depends on the choices of the other state, the social planner's first-stage problem of maximizing total welfare in (10) becomes equivalent to maximizing each state's welfare separately in the state's first-stage optimization problem under reverse conjoint federalism in (29), so each state makes an efficient choice as well. ■

Thus, inefficiencies in reverse conjoint federalism only arise through the externalities and through errors in the federal government's assessment of local production technology. The intuition is as follows. When states choose the output level, an inefficiency arises because they do not account for spillovers. When the federal government chooses the input policies to minimize total costs given the output levels, inefficiencies can arise through an inaccurate assessment of how input translates into output, or an inaccurate assessment of costs. However, when there are no externalities, input choices no longer depend on the particular cost function that is used as long as it is increasing; thus, cost assessments no longer matter.

4.2 Why delegate?

If the parameters lie somewhere between the extremes of no externality, in which case complete decentralization is first best, and no assessment errors, in which case complete centralization is first best, then it is possible that some form of partial decentralization, or delegation, may be second-best efficient. Before outlining possible reasons why delegation may be the optimal power distribution, I first establish when delegation cannot improve upon either complete decentralization or complete centralization.

Proposition 6 *Conjoint federalism is equivalent to federal control if the federal government's assessment of local production techology is correct (i.e., $f_i(\cdot) = f_{F,i}(\cdot)\ \forall i$) and if the production function $f_i(\cdot)$ is injective $\forall i$.*

Proof. *If $f_{F,i}(\cdot) = f_i(\cdot)\ \forall i$, then the federal government's desired output level will be realized under federal control, since the inputs $a_i^F(q)$ chosen based on equation (20) to meet the desired output levels q^F will produce the desired output in actuality. Thus, the desired solution $(a^F, q^{F,d})$ characterized by equations (20) and (21) is also the realized solution $(a^F, q^{F,r})$ under federal control. If, in addition, $f_i(\cdot)$ is injective $\forall i$, then, for any given vector of outputs, the Nash equilibrium input policies chosen by the states in conjoint federalism are the same as the input policies chosen by federal government in federal control, and are given by:*

$$a_i = \frac{1}{1-\alpha_i\alpha_j}\left(f_i^{-1}(q_i) - \alpha_i f_j^{-1}(q_j)\right)\ \forall i, j \neq i\ . \tag{35}$$

Since input as a function of the output vector is the same under both federal control and conjoint federalism, the federal government's choice of output is also the same. Thus, both scenarios yield the same solution for input and output. ■

Thus, if the government correctly assesses local production technology and if in each state only one value of effective input can implement any value of desired output, then federal control and conjoint federalism are equivalent. Intuitively, the only difference between federal control and conjoint federalism is that, given the output levels chosen by the federal government, input is chosen by the federal government in the former and by the state governments in the latter. There is therefore a divergence between the two scenarios whenever the federal government's assessment of how much input is needed to produce a given amount of output (i.e., its assessment of local production technology) is incorrect, or whenever the the non-cooperative Nash equilibrium choice of input policies to implement any given output vector is inefficient. Thus, if the federal government has inferior information about local production technology or if the same output can be implemented by different levels of input, then conjoint federalism has the potential to improve upon complete centralization. In contrast, unless there are neither externalities nor assessment errors, conjoint federalism *always* has the potential to improve upon complete decentralization because for generic functions the solutions arising under the two scenarios will differ.

Proposition 7 *Reverse conjoint federalism is equivalent to state control if the federal government's assessment of local production technology is correct (i.e.,* $f_{F,i}(\cdot) = f_i(\cdot)\ \forall i$*) and if either the production functions* $f_i(\cdot)$ *are injective* $\forall i$ *or externalities are absent (i.e.,* $\alpha_i = \alpha_j = 0$*).*

Proof. *If,* $\forall i$*,* $f_{F,i}(\cdot) = f_i(\cdot)$ *and either* $f_i(\cdot)$ *is one-to-one or* $\alpha_i = \alpha_j = 0$*, then the Nash equilibrium input policies* $a_i^S(q)$ *chosen under state control in equation (14) to implement any given output vector are equivalent to the cost-effective input policies* $a_c^R(q)$ *chosen under reverse conjoint federalism given by equation (28). Since the choice of input given output is the same under both scenarios, the states' choices of output will be the same as well.* ■

Thus, whenever there are externalities and errors in production function assessment, reverse conjoint federalism has the potential to improve upon complete decentralization. In contrast, unless there are neither externalities nor assessment errors, reverse conjoint federalism *always* has the potential to improve upon complete centralization because for generic functions the solutions arising under the two scenarios will differ.

There are two main reasons why delegation may be second-best efficient in the presence of cross-state externalities. First, if the preferences of the federal government differs from those of the local governments, then a commitment to delegate may enable the states to attend to local preferences while also allowing the federal government to partially internalize externalities. Second, if states have private information, then delegation may enable states to use some of their information while also enabling the federal government to partially internalize externalities. There are two possible reasons why information problems cannot be resolved by revelation mechanisms. First, communication costs might be prohibitively high. Second, if the preferences of federal and state governments differ, then states would refuse to reveal their private information to the federal government because the latter would use it to maximize its own utility rather than that of the former.

Thus, if the parameters lie somewhere between the extremes of no externality, in which case complete decentralization is first best, and no assessment errors, in which case complete centralization is first best, then it is possible that some form of partial devolution may be second-best efficient.

5 Delegation when the production functions are not injective

With injective (or one-to-one) production functions, only one pair of input policies can correctly implement any given vector of ouput levels. As a consequence, for any given output vector, the Nash equilibrium input policies are cost-effective. In particular, for any given vector (q_i, q_j) of outputs, if production functions were injective and the government's assessment of them correct, then input policies would always be given by:

$$a_i = \frac{1}{1-\alpha_i\alpha_j}(f_i^{-1}(q_i) - \alpha_i f_j^{-1}(q_j))\forall i, j \neq i \ , \tag{36}$$

irrespective of who has the power to choose them; in this case, input policies are fully determined by the choice of output level.

Now I examine the case when the production function is not injective and therefore when more than one level of effective input can produce any given level of output. When production functions are not one-to-one, then given any vector of output levels, the Nash equilibrium input policies that would be chosen by the states when the states can make the input decision would not be the cost effective input policy; thus, unlike with injective production functions, the noncooperative input policies that arise with non-injective production functions are inefficient.

What is the case for delegation when production functions are not injective? As seen in Proposition 6, when production functions are non-injective, federal control and conjoint federalism are no longer equivalent even when the government has perfect information about local production functions. Thus, it is possible that under certain circumstances conjoint federalism may be the unique second-best choice. However, if only agency problems were present but information probles were not, one would expect that delegation via conjoint federalism would fare even worse than federal control since input conditional on output would be efficiently chosen by the federal government in the former but not by the state governments in the latter.

Although delegation via conjoint federalism appears undesirable when both production functions are not injective and information problems nonexistent (i.e., $C_{F,i}(\cdot) = C_i(\cdot) \wedge f_{F,i}(\cdot) = f_i(\cdot)\ \forall i$), delegation via reverse conjoint federalism appears less so. Intuitively, if the federal government has perfect information, then it will choose the cost-effective input conditional on output, rendering reverse conjoint federalism more efficient than state control, all else equal. Moreover, because, unlike the federal government, states will use the correct preferences when choosing output, under certain conditions reverse conjoint federalism has the potential of dominating federal control as well. Thus, it appears likely that reverse conjoint federalism may be the second-best devolution scenario under certain circumstances when production functions are not injective and information problems absent.

Two institutional modifications could be made to ensure that when production functions are non-injective and information problems nonexistent, reverse conjoint federalism were not only second best, but first best as well. First, if the cost-sharing rules were constructed so that states were each at least local residual claimants, then states would choose the first-best output. Since the federal government would choose the efficient input conditional on output, the first best would be implemented. One such cost-sharing rule would be to make each state pay an amount $\varphi(a_i, a_j)$ given by:

$$\varphi(a_i, a_j) = C_i(a_i) + C_j(a_j) - \frac{1}{2}\left(C_i(a_i^P) + C_j(a_j^P)\right), \tag{37}$$

instead of only their own local costs $C_i(a_i)$ or $C_j(a_j)$, so that each state internalizes the effect of its output choice on the input cost of the other state. Under such a cost-sharing rule, each state's second-stage input choice problem would be given by:

$$\widetilde{a_i}(q) = \arg\min_{a_i} \left\{ \varphi(a_i, a_j) \mid a_i = \frac{1}{1-\alpha_i\alpha_j}(A_i - \alpha_i A_j),\ A_i \in f_i^{-1}(q_i) \forall i, j \neq i \right\}, \tag{38}$$

and each state's first-stage output choice optimization problem becomes:

$$\widetilde{q_i} = \arg\max_{q_i} V_i(q_i) - \varphi(\widetilde{a_i}(q), \widetilde{a_j}(q)) . \tag{39}$$

The solution to (39) is equivalent to the solution to the social planner's first-stage output choice problem (10); as a consequence, the first best can be achieved.

A second institutional modification that would guarantee that reverse conjoint federalism were first best would be to make output contractible when the federal government has power. In other words, a_i is never observable or verifiable; q_i is not observable or verifiable unless the federal government is included in the regulatory hierarchy. Under these assumptions, the distribution of power is important because it determines which tier of government can make decisions about input, decisions which are not contractible, and because it determines whether or not output is contractible. One justification for why granting the federal government power would render output contractible is that unlike individual states which each have an incentive to obfuscate its output level from the other because of spillovers, the federal government, which accounts for the utility of both states, albeit possibly incorrectly, has no such incentive and can standardize measurement equipment to observe and verify output. If, in addition, the federal government had no information problems, then its measurement of output would be correct and states would be able to contract on it. Thus, when the federal government has power but delgates the output choice to states in reverse conjoint federalism, states can contract with each other to chooise the welfare-maximizing output. If the federal government assesses both cost and production functions correctly, then it will also choose the welfare-maximizing input given output. As a consequence, the first-best outcome can be implemented.

Thus, with either appropriate cost-sharing rules or with the contractibility of output when the federal government has power, reverse conjoint federalism is the first-best decentralizaiton scenario when production functions are not injective and when agency problems are present but information problems are not.

6 Application to ozone smog regulation

I now examine the problem of multi-jurisdictional ozone smog regulation in light of my results. The principal ingredient of smog, tropospheric ozone is the most difficult to control of the six criteria pollutants for which United States Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS) have been established (Chang & Suzio, 1995). Among ozone's adverse effects on humans are labored breathing, impaired lung functions and possible long-term lung damage. Ozone exposures have also been associated with a wide range of vegetation effects, including visible foliar injury, growth reductions, and yield loss in agricultural crops; growth reductions in seedlings and mature trees; and impacts at forest stand and ecosystem levels (EPA, 1997b; Sillman, 1995). A secondary pollutant, ozone is not emitted directly but is formed in ambient air by chemical reactions involving nitrogen oxides (NOx), which consist of nitrogen oxide (NO) and nitrogen dioxide (NO2), and volatile organic compounds (VOCs).

The current division of regulatory responsibility in the United States is what I have termed in this paper conjoint federalism: the federal government to set a uniform ambient air quality standard that each state must implement policies to meet (Farrell & Keating, 1998). In the terminology of my model, the federal government chooses the output levels while the states choose invidual input policies, where output is clean air[14] and input is precursor reduction. However, it appears that this current policy is neither efficient nor effective; as of 1998, 130 million persons in the U.S. lived in areas violating the new 8-hour standard of 0.08 ppm (EPA, 2000). Moreover, Lin, Jacob and Fiore (2001) provide evidence that, except in the Southwest, air quality improvements from the 1980s to the 1990s have leveled off in the past decade. Based on my model, is conjoint federalism the second-best decentralization choice for ozone smog?

The regulation of ozone smog is difficult for several reasons. First, there are externalities involved in ozone reduction. These externalities arise because ozone precursors are transboundary pollutants. For instance, "a reduction in transport into the New York area associated with upwind emissions reductions on the order of 75 percent for NOx and 25 percent for VOC along with local VOC and NOx reductions may be needed for attainment in New York"(EPA, 1997a, II.B.4). NOx and VOC emissions from up to 1000 km away have significant impacts on ambient ozone concentrations (Lin, 2010a). Externalities arising from the transboundary nature of ozone precursors thus complicate ozone regulation. Owing to these externalities, individual cities do not always have direct control of their own attainment of the ozone standard. In my model, the externalities resulting from input captures the transboundary nature of the ozone precursors.

A second reason why ozone regulation is difficult is that ozone production is influenced

[14]Output in my model is a good, not a bad. In the context of ozone, output can be measured as the negative of the ozone concentration or as the difference between some extremely high level of ozone and the actual level of ozone.

by a variety of meteorological factors, including temperature, cloud cover, wind speed, and solar intensity (Olszyna et al., 1997; Smith & Adamski, 1998). Such meteorological factors can mitigate the beneficial effects of reductions in anthropogenic emissions on air quality (Lin, Jacob & Fiore, 2001). Thus, exogenous, stochastic factors may affect a regulator's ability to reduce ozone concentrations. If local governments have better or more information about these local meteorological factors than the federal govenrment does, then these factors may be a source of private information in local ozone production functions.

A third consideration for ozone pollution control is the background level of ozone. This background is the ozone concentration that would prevail in the absence of domestic anthropogenic emissions (Altshuller & Lefohn, 1996; Lin, Jacob, Munger & Fiore, 2000). The background level of ozone is important for several reasons. First, its level can affect the attainability of air quality standards. According to the EPA (1997a, II.B), during a summertime ozone episode in the eastern United States, "the emissions from numerous small, medium and large cities, major stationary sources in rural areas, as well as natural sources, combine to form a 'background' of moderate ozone levels ranging from 80 to 100 ppb of which 30 to 40 ppb may be due to natural sources. . . .Because this level of background ozone is so close to the NAAQS, even a small amount of locally-generated ozone will result in an exceedance." A second reason background ozone is important is that its actual level is uncertain and may be changing over time (Lin et al., 2000). If local governments have more or better information about lcoal background levels thatn the federal government does, then background levels would be a source of private information for the states.

A fourth reason why ozone regulation is difficult is that the rate of ozone production is a nonlinear and non-monotonic function of NOx and VOC concentrations. There are two different photochemical regimes: a NOx-limited regime, in which the rate of ozone formation increases with increasing NOx and is insensitive to changes in VOC; and a VOC-limited regime, in which the rate of ozone formation increases with increasing VOC and may even decrease with increasing NOx (Sillman, 1999). Thus, the reduction of one precursor may have opposing effects on ozone concentrations depending on the concentrations of both precursors. Moreover, different cominations or precrusor levels may yield the same amount of ozone. In other words, the production functions are not injective.

Externalities, private information in production functions, private information in background levels, and non-injective production functions thus appear to be some of the key features of the ozone regulation problem. According to my model, all these features suggest that delegation may be preferred to either extreme of federal control or state control, although the actual form of delegation that should be chosen may depend on the relative importance of these features. Since externalities are large and information problems in production technology and/or background levels may be present, conjoint federalism – the distribution of power currently in place – may indeed be the second-best optimal choice. However, the non-injective nature of the ozone production functions suggest that if the information problems were absent, reverse conjoint federalism may instead be the second-best choice. Moreover, if clever cost-sharing rules were implemented or if including the federal government in the regulatory hierarchy could enable states to contract on output, then reverse conjoint federalism may actually achieve the first best.

7 Conclusion

In this paper, I develop a model of the regulatory game within and between different tiers of government to investigate the optimal allocation of regulatory power for public goods provision and outline circumstances under which partial devolution is the most efficient allocation of regulatory power. The tradeoff is between the federal government's ability to internalize externalities and implement the cooperative solution on the one hand and its failure to correctly account for local benefits, costs, and/or production technology on the other.

My results show that the second best choice of decentralization scenario depends on the extent of the externality and of the severity of the agency and/or information problems, and that, under certain values of the parameters, partial decentralization may be the most efficient. When state governments have better information about the local production technology than the federal government does, a case for delegation via conjoint federalism can be made. When the federal government has an agency problem or when state governments have better information about local benefits or local costs, a case for delegation via reverse conjoint federalism can be made.

Moreover, reverse conjoint federalism may be second-best when production functions are not injective and information problems are absent; if, in addition, either appropriate cost-sharing rules are implemented or output becomes contractible when the federal government has power, reverse conjoint federalism can actually achieve the first-best outcome. Thus, for the regulation of ozone smog, since ozone production functions are not strictly monotone, it is possible that with some institutional modifications, the first-best output could be implemented via reverse conjoint federalism.

My results have important implications for the issue of optimally distributing governmental power in the provision of public goods as well as for any problem of organizational choice in the presence of interjurisdictional externalities.

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