Optimal governmental decentralization for environmental regulation

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Preliminary—Comments welcome

1 Introduction

"Environmental federalism is a complicated issue. Both theory and practice suggest the existence of real tensions and a certain ambivalence about the roles of the different levels of government in environmental management" (Oates, 2001, p. 31). The optimal degree of decentralization for the provision of public goods has been of interest to economists at least since the time Tiebout (1956), Olson (1969) and Oates (1972) published their pioneering works. When applied to the American political system, the issue of federalism, defined as "the distribution of power in an organization (as a government) between a central authority and the constituent units" (Webster's, 1991, p. 454), is often framed as the appropriate division of regulatory responsibility between the federal government on the one hand and the state or local governments on the other. In this paper, I investigate the optimal degree of decentralization in the governmental regulation of transboundary pollutants such as ozone smog.

In determining the optimal distribution of 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, environmental management even when the federal government is constrained to treat all local districts uniformly. First, centralized control can internalize any externalities that exist among local districts. Such an externality arises with transboundary pollutants 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

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its pollution control policy on its downwind (or downstream) neighbor than a central government under a centralized system would.

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. In contrast, it is often argued, local control may lead to the underprovision of public goods because local officials would set excessively lax environmental standards in order to attract businesses to and create jobs in their respective districts (Oates, 2001). 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).

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 environmental justice grounds, 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 environmental damages and pollution-control techniques, 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.

When the federal government is able to treat local districts non-uniformly, 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. In particular, the federal government may be able to impose different standards on different states in order to best internalize any externalities among the states; it may also be able to exploit the information it acquires from all the states to best filter out common weather shocks in order to better determine the effort levels of individual states.

Although centralized control has many advantages, a case can be made for the opposite extreme of completely decentralized management as well, even when the federal government can treat local districts non-uniformly. One advantage of local control is that local governments are better able to tailor their policy to the preferences of their particular local constituents. A second possible advantage of decentralization 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. Third, local governments may have better or more information about local abatement costs, local pollution control technology and/or any local environmental conditions that may affect the effectiveness of pollution abatement efforts. A fourth reason why decentralization may be preferred is that imperfections in the decision making institutions at the federal level may dissipate some of the potential benefits of centralization; Besley and Coate (1999) present a model in which decentralization may outperform centralization even when the central government is allowed to provide non-uniform levels of local public goods.

There are thus many tradeoffs between centralized and decentralized systems of public goods provision. This paper presents a model that captures parametrically these tradeoffs, enabling both a comparison of the extreme cases of federal control and local control with each other and with several forms of partial delegation, as well as a characterization of the optimal degree of decentralization. My results show that in some cases partial delegation can be preferred to both complete centralization and complete decentralization. I also find that, in certain cases, the particular form of delegation currently used to regulate ozone smog in the United States can be less efficient than either state control or federal control, and that a reverse form of delegation may be more efficient than all three. Although I apply my model to ozone smog regulation in particular, the implications of my model are generalizable to other public goods and, even more generally, to any problem of organizational choice in the presence of interjurisdictional externalities.

2 Previous Literature

My research relates to several existing branches of literature in contract theory. The first branch of literature is that on moral hazard in teams. This line of work considers models with multiple agents and one principal. Such models fall in two general categories. First, if neither the efforts nor the performance levels of the individual agents are observed, then there is an externality: an improvement in aggregate performance cannot be traced back to individual efforts (Bolton & Dewatripont, forthcoming). Examples of models in which only output is observed include those of Holmstrom (1982) and Legros and Matthews (1993). Second, when individual performance levels are observable and contractible, then the key issue is the extent to which an individual's compensation should depend on other agents' performances (Bolton & Dewatripont, forthcoming). An extreme form of relative performance evaluation, tournaments, has been analyzed by Lazear and Rosen (1981) and by Green and Stokey (1983).

A second branch of theoretical literature that relates to my research is that on common agency. In these models, there are several principals who simultaneously and independently attempt to influence a common agent. For example, Bernheim and Whinston (1986) find that under common agency, aggregate schemes always implement the equilibrium action at minimum cost. They also find that noncooperative behavior induces an efficient and potentially second-best action choice if and only if collusion among the principals would implement the first-best action at the first-best level of cost.

A third branch of related theoretical literature is that on hierarchies. One form of hierarchy is induced by the ability of the principal to hire a supervisor to obtain additional information about the agent. Such principal-supervisor-agent models often incorporate the possibility of collusion between the supervisor and the agent (see e.g. Tirole, 1986 and Baron & Besanko, 1984). A second form of hierarchy exists in large, multi-tier organizations in which an employee at a given intermediate tier is both the subordinate of an employee from a higher tier and the supervisor for employees from a lower tier. Qian (1994) studied incentives and loss of control in hierarchies to determine the optimal degree of decentralization in a firm.

While the above-mentioned work on moral hazard in teams, common agency and hierarchies reside in the realm of complete contracts, my work draws most heavily on the incomplete contracting literature which evolved from the transactions cost theories of Coase (1937), Williamson (1975), and Klein, Crawford and Alchian (1978), and which was later formalized by, among others, Hart (1995). In particular, my model of the optimal governmental structure is an application of Hart and Holmstrom's (2002) model of market structure and firm scope to a political context.

My research draws upon the literature not only in contract theory, but also in public economics as well. My examination of the appropriate level of regulation for ozone smog is a particular application of the issue of federalism. There is a thriving literature on the optimal scale of public good provision (see e.g. Oates, 1972). Oates (2001) examines the roles of different levels of government in environmental management; Bui (1998) investigates multi-jurisdictional acid rain abatement. In addition to these studies of federalism, my research also relates to the literature on the optimal policy instrument for pollution control, a literature pioneered by Weitzman (1974).

3 Basic Model

3.1 Framework

To gain some intuition about why some forms of partial decentralization may be preferred to both centralized and decentralized control, I present a basic model that focuses on the tradeoff between the ability of the federal government to internalize externalities on the one hand and its failure to account for local preferences, costs and production technology on the other. In this simple model, there is a federal government and two state governments. For now, I assume that individuals are homogeneous within states but differ between the two states.

Let q_i denote the environmental quality (or environmental output) in state i. Environmental quality is higher when pollution levels are lower. The aggregate benefit to residents of state i of environmental quality q_i is $V_i(q_i)$.[2]

[2] For the moment, I remain agnostic about how individual environmental quality benefits are aggregated to the state level.

While each state government uses its correct respective aggregate benefit function in assessing the benefits of environmental quality, the federal government does not. For each state i, the federal government uses $V_{F,i}(q_i)$ as the aggregate state benefit instead of $V_i(q_i)$. One possible reason why the federal government incorrectly assesses local benefits is that its preferences differ from those of the local constituents; another possible reason is that the federal government would like to account for local preferences but is unable to correctly measure what these preferences are and therefore uses an incorrect estimate of them. For now, I remain agnostic about the actual reason why federal and state preferences may differ; I merely allow for the possibility that they do. Both $V_i(\cdot)$ and $V_{F,i}(\cdot)$ are nondecreasing and concave. Benefits are measured in terms of money equivalents.

The pollution abatement effort of state i is given by a_i. This state-level effort level can be conceived of as representing an aggregated abatement effort of all the firms in the state. For each state i, exerting effort a_i imposes a cost $C_i(a_i)$. Cost functions may vary by state depending on the distribution of firms in each state. The federal government's estimate of the state i's cost function is $C_{F,i}(\cdot)$. Both $C_i(\cdot)$ and $C_{F,i}(\cdot)$ are nondecreasing and convex.

Owing to externalities in abatement effort, each state i's environmental quality is a function of both its own effort and the effort of the other state j, and is given by:

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

where $f_i(\cdot)$ reflects state i's technology of translating effort into output, where $\alpha_i \in [-1, 1]$ measures the extent of the externality, and where $a_i + \alpha_i a_j$ is the effective effort in state i. I assume that the externalities $\{\alpha_i\}_{i=1,2}$ are known to all governments. The federal government's assessment of state i's technology is given by $f_{F,i}(\cdot)$. I assume that just as the federal government does not know the states' production function, the states are unaware of the federal government's assessment and instead use their actual production function as their assessment of the federal government's assessment.

I model governmental power as the right to make decisions about environmental quality output q_i and about effort level a_i. This notion of power is analogous to the notion of ownership propounded by Hart and Holmstrom (2002); in their terminology, the level of government with power is the "boss". Operating in the contractual incompleteness paradigm, I assume that neither the output q_i nor the effort level a_i is contractible ex ante or ex post. In other words, q_i and a_i are neither observable nor verifiable. Because neither output nor effort is contractible, government decisions about output and effort are not contractible. As a consequence, it matters which tier of government has power.

I choose the incomplete contracting framework for two main reasons. First, the assumption that neither effort nor output is contractible seems reasonable in the context of environmental quality. Because pollution abatement requires enforcement, and because the tier of government with power will not necessarily enforce any effort levels imposed upon it from outside, bosses cannot contract on each other's effort levels. Likewise, an individual state's environmental quality is not contractible because it is difficult to measure or monitor with certainty and can therefore be obscured by the state's boss from the boss of other states. A second reason why I assume contracts are incomplete is to provide a possible justification for the existence of a federal government. If contracts were complete, then individual state governments could coordinate by contracting on output or effort and then dividing the surplus through transfers or side payments; as a consequence, no federal government would be needed. It is precisely because contracts are incomplete and coordination is no longer possible that a federal government may be necessary.

The utility function for each state i is given by:

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

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

$$\begin{aligned} W &= \sum_i U^i \\ &= \sum_i [V_i(q_i) - C_i(a_i)] \ . \end{aligned} \tag{3}$$

A social planner P would use total welfare W as her objective function. In contrast, because the federal government uses its own assessment of the costs and benefits, the federal government's objective function is given by:

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

In the framework of Hart and Holmstrom (2002), central control when the federal government assesses costs and benefits differently from the state governments is analogous to integration when the boss is an outsider with preferences different from those of either of the two individual units that were merged.

3.2 Social Optimum (P control)

The social planner chooses the effort and output levels of both states simultaneously to maximize total welfare. The solution to her problem yields the socially efficient choice of environmental quality output and pollution abatement effort levels. Formally, her problem is given by:

$$\max_{\{a_i, q_i\}_i} W = \sum_i [V_i(q_i) - C_i(a_i)] \tag{5}$$

$$\text{s.t. } q_i = f_i(a_i + \alpha_i a_j) \ \ \forall i, j \neq i \ . \tag{6}$$

Solving the constraints for effort in terms of output yields

$$a_i = \frac{1}{1-\alpha_i\alpha_j}(f_i^{-1}(q_i) - \alpha_i f_j^{-1}(q_j)) \quad \forall i, j \neq i \ . \tag{7}$$

Substituting in the above expression for effort, the social planner's problem reduces to:

$$\max_{\{q_i\}_i} \sum_i [V_i(q_i) - C_i(\frac{1}{1-\alpha_i\alpha_j}(f_i^{-1}(q_i) - \alpha_i f_j^{-1}(q_j)))] \ . \tag{8}$$

Taking first-order conditions and making use of the implicit function theorem, one gets:

$$V_i'(q_i) = \frac{C_i'(a_i) - \alpha_j C_j'(a_j)}{f_i'(a_i + \alpha_i a_j) \cdot (1-\alpha_i\alpha_j)} \quad \forall i, j \neq i \ . \tag{9}$$

This first-order condition can be interpreted as setting the marginal social benefits of output to the marginal social costs of the effort needed to achieve that output. Assuming that second-order conditions are satisfied,[3] equations (7) and (9) completely characterize the socially efficient effort and output levels (a^P, q^P), where $a^P = (a_i^P, a_j^P)$ and $q^P = (q_i^P, q_j^P)$. This 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.

3.3 State (S) control

Under decentralized, or state, control, each state chooses its own output and effort levels given the other state's choices. In the noncooperative Nash equilibrium that ensues, each state's choice is a best response to the other state's choice. Using the terminology of the firm boundary literature, if the states are individual plants or units, then state control is the market structure in which the individual firms are non-integrated. Each state i's problem is given by:

$$\max_{a_i, q_i} U^i = V_i(q_i) - C_i(a_i) \tag{10}$$

$$\text{s.t. } q_i = f_i(a_i + \alpha_i a_j) \ , \tag{11}$$

where the other state j's effort a_j and output q_j are taken as given. Because each state's effort must satisfy the constraint (11), effort as a function of output

[3] The second-order conditions would be automatically satisfied if the set $\{a_i, a_j, q_i, q_j | q_i = f_i(a_i + \alpha_i a_j) \quad \forall i, j \neq i\}$ 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.

is once again given by equation (7).[4] After substituting the equation for effort back into state i's problem, the first-order condition for each state i is given by:

$$V_i'(q_i) = \frac{C_i'(a_i)}{f_i'(a_i + \alpha_i a_j)} \quad , \tag{12}$$

Assuming that second-order conditions are satisfied,[5] the effort and output levels (a^S, q^S) that arise in complete decentralization are characterized by equations (7) and (12). Under state control, local preferences, costs and technology are taken into account but externalities are not. In particular, when no externalities are present (i.e., $\alpha_i = \alpha_j = 0$), then the first-order equation for the first best, equation (9), becomes equivalent to that for state control, equation (12). In other words, in the absence of externalities, complete decentralization achieves the first best.

3.4 Federal (F) control

Under centralized, or federal, control, the federal government chooses the output and effort levels for all states simultaneously to maximize its utility. Using the terminology of the firm boundary literature, if the states are individual plants or units, then federal control is the market structure in which the individual firms are integrated and the boss is an outsider. The federal government's problem is given by:

$$\max_{\{a_i, q_i\}_i} U^F = \sum_i [V_{F,i}(q_i) - C_{F,i}(a_i)] \tag{13}$$

$$\text{s.t. } q_i = f_{F,i}(a_i + \alpha_i a_j) \quad \forall i, j \neq i \ . \tag{14}$$

Thus, the federal goverment's assessment of each state i's local benefits $V_{F,i}(\cdot)$, costs $C_{F,i}(\cdot)$, and production technology $f_{F,i}(\cdot)$ may potentially differ from the actual local benefits $V_i(\cdot)$, costs $C_i(\cdot)$, and production technology $f_i(\cdot)$, respectively.

Solving the constraints for effort in terms of output yields

[4] I assume for mathematical simplicity that the states know each other's benefit, cost and production functions so that a Nash equilibrium arises under a decentralized system. Thus, in this model, states know each other's benefit, cost and production functions but not those used by the federal government, and the federal government does not know those of the states. Any particular government's choice of effort and output levels, however, is unobservable and verifiable to any other government, including those from the same tier. As a possible extension to my model, I can consider the case in which states do not know each other's benefit, cost and/or production technology and solve for the consequent Bayesian equilibrium.

[5] The second-order conditions would be automatically satisfied if, for each state i, the set $\{a_i, q_i | q_i = f_i(a_i + \alpha_i a_j)\}$ were convex. As before, 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.

$$a_i = \frac{1}{1-\alpha_i\alpha_j}(f_{F,i}^{-1}(q_i) - \alpha_i f_{F,j}^{-1}(q_j)) \quad \forall i, j \neq i \ . \tag{15}$$

Note that if the federal government incorrectly assesses local production technology, then this equation for effort is different from that arising both in the social optimum and in state control. Substituting in the above expression for effort into the federal government's problem, the first-order conditions yield:

$$V'_{F,i}(q_i) = \frac{C'_{F,i}(a_i) - \alpha_j C'_{F,j}(a_j)}{f'_{F,i}(a_i + \alpha_i a_j) \cdot (1-\alpha_i\alpha_j)} \quad \forall i, j \neq i \ . \tag{16}$$

Assuming that second-order conditions are satisfied,[6] equations (15) and (16) characterize the federal government's desired effort and output levels $(a^F, q^{F,d})$. However, because the federal government incorrectly assesses local technology, the realized output that arises based on its effort choice is not its desired output but is instead given by the output produced when the actual production technology is applied to a^F:

$$q_i^{F,r} = f_i(a_i^F + \alpha_i a_j^F) \ . \tag{17}$$

Thus, under complete centralization, the effort 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 assessment of 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).

3.5 Conjoint Federalism (C)

When externalities exist and when the federal government's assessments of local conditions diverge from the truth, 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. With delegation, the federal government as boss commits to allocating some of its power to its subordinate managers at the state level. In one form of delegation, the federal government chooses output first and then delegates the effort choice to the respective states.[7] 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.

[6] The second-order conditions would be automatically satisfied if the set $\{a_i, a_j, q_i, q_j | q_i = f_{F,i}(a_i + \alpha_i a_j) \ \ \forall i, j \neq i\}$ were convex.

[7] If the states were to choose the effort levels 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 effort levels first before the federal government chooses the output levels is therefore equivalent to complete decentralization. Thus, it need not be separately analyzed.

To determine the effort and output levels that arise under conjoint federalism, one can solve the sequential game backwards. In the second stage of the game, each state i chooses its effort level a_i given the vector of outputs $q^C = (q_i^C, q_j^C)$ chosen by the federal government and the effort level a_j^C chosen by the other state j. Assuming that each state must achieve with equality the output level dictated by the federal government, and given the technology that translates effort into output, each state i chooses as its effort level:

$$a_i = f_i^{-1}(q_i^C) - \alpha_i a_j^C \quad . \tag{18}$$

The Nash equilibrium effort levels are thus given by:

$$a_i^C = \frac{1}{1-\alpha_i\alpha_j}(f_i^{-1}(q_i^C) - \alpha_i f_j^{-1}(q_j^C)) \quad \forall i, j \neq i \ . \tag{19}$$

In the first stage of the game, the federal government chooses the output levels to maximize its utility subject to the state reaction functions (19). Its problem is thus given by:

$$\max_{\{q_i\}_i} U^F = \sum_i [V_{F,i}(q_i) - C_{F,i}(a_i)] \tag{20}$$

$$\text{s.t. } a_i = \frac{1}{1-\alpha_i\alpha_j}(f_i^{-1}(q_i) - \alpha_i f_j^{-1}(q_j)) \quad \forall i, j \neq i \ . \tag{21}$$

After substituting the constraint into the objective function, the first-order conditions are:

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

Thus, assuming that second-order conditions are satisfied, equations (19) and (22) characterize the effort and output levels (a^C, q^C) that arise under conjoint federalism. While (19) is equivalent to the analogous function (7) from both the first best and state control, the first-order condition (22) is equivalent to the first-order condition (16) arising in federal control. Because it combines characteristics from state control and federal control, conjoint federalism may potentially dominate both.

3.6 Reverse Conjoint Federalism (R)

In addition to conjoint federalism, an alternate form of delegation to consider would be to have the states choose the output first while the federal government chooses the effort levels second.[8] I will call this particular form of partial decentralization reverse conjoint federalism.

In the second stage of reverse conjoint federalism, the federal government chooses effort levels given the environmental quality levels chosen by the states. Since the federal government believes that effort levels translate to output through the following production technology:

$$q_i = f_{F,i}(a_i + \alpha_i a_j) \ \ \forall i, j \neq i \ . \tag{23}$$

and assuming that the federal government intends to meet the output levels $q^R = (q_i^R, q_j^R)$ dictated by the states with equality, it chooses effort levels to achieve q^R, that is:

$$a_i^R = \frac{1}{1-\alpha_i\alpha_j}(f_{F,i}^{-1}(q_i^R) - \alpha_i f_{F,j}^{-1}(q_j^R)) \quad \forall i, j \neq i \ . \tag{24}$$

Since the states believe that the federal government chooses effort levels based on equation (7), not equation (24), each state solves the following problem in the first stage of reverse conjoint federalism:

$$\max_{q_i} U^i = V_i(q_i) - C_i(a_i) \tag{25}$$

$$\text{s.t. } a_i = \frac{1}{1-\alpha_i\alpha_j}(f_i^{-1}(q_i) - \alpha_i f_j^{-1}(q_j)) \quad \forall i, j \neq i \ . \tag{26}$$

After substituting the constraint into the objective function, the first-order conditions are:

$$V_i'(q_i) = \frac{C_i'(a_i)}{f_i'(a_i + \alpha_i a_j) \cdot (1-\alpha_i\alpha_j)} \quad \forall i, j \neq i \ . \tag{27}$$

Thus, assuming that second-order conditions are satisfied, equations (24) and (27) characterize the desired effort and output levels $(a^R, q^{R,d})$ that arise under reverse conjoint federalism. However, because the federal government incorrectly assesses local technology, the realized output that arises based on its effort choice is not its desired output but is instead given by the output produced by from applying the actual technology to a^R:

[8] If the federal government were to choose the effort levels first, then the output levels would already be determined and therefore could no longer be chosen independently. The form of delegation in which the federal government chooses effort levels first and the state governments choose the output levels second is therefore equivalent to complete centralization. Thus, it does not need to be separately analyzed.

$$q_i^{R,r} = f_i(a_i^R + \alpha_i a_j^R) \quad . \tag{28}$$

Thus, under complete centralization, the effort and output levels that are realized are $(a^R, q^{R,r})$. In comparing the first-order condition (27) arising from reverse conjoint federalism with the first-order conditions (12) and (16) arising from state control and federal control, respectively, it appears that reverse conjoint federalism accounts for externalities better than the former does and accounts for local conditions better than the latter does. It is therefore possible that, under certain values of the parameters, reverse conjoint federalism is more efficient than both extremes.

3.7 General results

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 basic model yields several general results.

Proposition 1 *In the absence of externalities (i.e., when $\alpha_i = \alpha_j = 0$), state control achieves the first best (i.e., $W^S = W^P$).*

Proof. *If $\alpha_i = \alpha_j = 0$, then two equations (7) and (12) that characterize the solution under state control become equivalent to the two equations (7) and (9) that characterize the social optimum.* ■

Intuitively, state control is efficient when there are no spillovers because if one state's choices has no effect on the other, then no inefficiencies arise from letting the states choose their own effort and output.

Proposition 2 *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 $f_{F,i}(\cdot) = f_i(\cdot)\ \forall i$), then both (i) federal control and (ii) conjoint federalism achieve the first best (i.e., $W^F = W^C = W^P$).*

Proof. *(i) 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 efforts chosen based on equation (15) to meet the desired output levels will produce the desired output in actuality, via equation (17). Thus, the desired solution characterized by equations (15) and (16) is also the realized solution under federal control. Further, if, in addition,$\forall i$, $V_{F,i}(\cdot) = V_i(\cdot)$ and $C_{F,i}(\cdot) = C_i(\cdot)$, then the two equations (15) and (16) characterizing the desired effort and output levels under federal control become equivalent to the two equations (7) and (9) that characterize the socially optimal effort and output levels. Since the desired effort and output levels are achieved, the realized solution under federal control is first best.*

(ii) If, $\forall i$, $V_{F,i}(\cdot) = V_i(\cdot)$, $C_{F,i}(\cdot) = C_i(\cdot)$ and $f_{F,i}(\cdot) = f_i(\cdot)$, then the two equations (19) and (22) characterizing the solution under conjoint federalism become equivalent to the two equations (7) and (9) characterizing the solution under the social optimum. ■

Thus, both federal control and conjoint federalism are efficient if the federal government does not err in assessing local conditions. The intuition is the following. When it correctly accounts for all local conditions, the federal government makes the first best choices for both effort and output. Thus, output and effort under federal control and output under conjoint federalism are first-best efficient. Moreover, since the states always make the efficient choice of effort needed to implement any given output level, if the outputs given are first best, then the effort choices are first best as well. Thus, effort levels in conjoint federalism are also first-best efficient. As a consequence, the solutions under federal control and conjoint federalism are efficient.

Proposition 3 *When there are neither externalities nor assessment errors, 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.* ■

That is, when there is no source of inefficiency at either extreme of decentralization, then both extremes are efficient, as are all intermediate forms of partial decentralization in between as well.

Proposition 4 *Federal control and conjoint federalism are equivalent whenever the federal government's assessment of local production techology is correct (i.e., $f_i(\cdot) = f_{F,i}(\cdot)\ \forall i$).*

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 efforts chosen based on equation (15) to meet the desired output levels will produce the desired output in actuality, via equation (17). Thus, the desired solution characterized by equations (15) and (16) is also the realized solution under federal control. Moreover, when $f_{F,i}(\cdot) = f_i(\cdot)\ \forall i$, these two equations become equivalent to the two equations (19) and (22) that characterize the solution under conjoint federalism.* ■

Thus, if the government correctly assesses local production technology, 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, effort 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 effort is needed to produce a given amount of output (i.e., its assessment of local production technology) is incorrect.

Proposition 5 *When there are neither externalities nor errors in the federal government's assessment of local production technology, reverse conjoint federalism achieves the first best (i.e., $W^R = W^P$).*

Proof. *If $f_{F,i}(\cdot) = f_i(\cdot)\ \forall i$, then the state governments' desired output levels will be realized under reverse conjoint federalism, since the efforts chosen based on equation (24) to meet the states' desired output levels will produce the desired output in actuality, via equation (28). Thus, the desired solution characterized by equations (24) and (27) is also the realized solution under reverse conjoint federalism. Further, if, in addition, $\alpha_i = \alpha_j = 0$, then the two equations (24) and (27) characterizing the desired effort and output levels under reverse conjoint federalism become equivalent to the two equations (7) and (9) that characterize the socially optimal effort and output levels. Since the desired effort and output levels are achieved, the realized solution under reverse conjoint federalism is first best.* ■

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 effort levels given the output levels, the only inefficiency that arises is that through its inaccurate assessment of how effort translates into output; neither its assessment of local benefits nor its assessment of local costs affects its choice of effort.

In addition to the general results presented above, one further observation should be noted. 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 delegation may be second-best efficient. In order to better intuit the results arising from intermediate values of the parameters, I now consider a special case of my basic model.

4 Special case: Log utility, linear costs and linear production

4.1 Analytic solution

To compare the outcomes that arise under the various decentralization scenarios, I use a special case of my basic model yields relatively simple analytic solutions: log utility, linear costs and linear production. More specifically, I assume that the actual local benefit, cost and production functions for each state i are given by:

$$
\begin{aligned}
V_i(q_i) &= v_i \ln(q_i) \\
C_i(a_i) &= c_{0i} + c_{1i} a_i \\
f_i(a_i + \alpha_i a_j) &= f_{0i} + f_{1i} \cdot (a_i + \alpha_i a_j) \ .
\end{aligned}
$$

In the production equation $f_i(\cdot)$, the constant f_{0i} can be interpreted as the background level of environmental quality; that is, the level of environmental quality that would arise in the absence of any anthropogenic effort.[9] The slope f_{1i} can be interpreted as the marginal productivity of effective effort, where the effective effort in one state includes not only that state's own effort but also any spillover effects of the effort exerted by the other state. The federal government's perceptions of local benefit, cost and production functions for each state i are given by:

$$
\begin{aligned}
V_{F,i}(q_i) &= (v_i + \varepsilon_i^v) \ln(q_i) \\
C_{F,i}(a_i) &= c_{0i} + (c_{1i} + \varepsilon_i^c) a_i \\
f_{F,i}(a_i + \alpha_i a_j) &= f_{0i} + \varepsilon_i^{f_0} + (f_{1i} + \varepsilon_i^{f_1}) \cdot (a_i + \alpha_i a_j) \ ,
\end{aligned}
$$

where ε_i^v, ε_i^c, $\varepsilon_i^{f_0}$, and $\varepsilon_i^{f_1}$ measure errors in the federal government's assessment of state i's local benefits, costs, background, and marginal product, respectively. Thus, there are two ways in which the federal government can err in assessing the local production technology: it can err in assessing the local background environmental quality, or it can err in assessing the local marginal productivity of effective effort. I assume that, $\forall i$, $v_i > 0$, $v_i + \varepsilon_i^v > 0$, $c_{1i} > 0$, $c_{1i} + \varepsilon_i^c > 0$, $f_{1i} > 0$, and $f_{1i} + \varepsilon_i^{f_1} > 0$, so that both actual and assessed benefits, marginal costs, and marginal product are all positive. Since benefit functions are concave, cost functions are convex and constraint sets are convex, second-order conditions need not be considered; first-order conditions are both necessary and sufficient for characterizing solutions to the constrained maximization problems faced by the various agents in my model. Under these functional form assumptions, the chosen effort a_i, desired output q_i^d and realized output q_i^r that arise for each state i under the different decentralization scenarios are as follows:

[9] Background environmental quality levels are an important consideration for the design of pollution control strategies; their actual levels are often the subject of considerable debate, particularly if these levels may be changing over time (for the case of ozone smog, see Lin, Jacob, Munger & Fiore, 2000, & references therein).

	a_i
P	$\frac{v_i}{c_{1i}-\alpha_j c_{1j}} - \frac{f_{0i}}{f_{1i}\cdot(1-\alpha_i\alpha_j)} - \frac{\alpha_i v_j}{c_{1j}-\alpha_i c_{1i}} + \frac{\alpha_i f_{0j}}{f_{1j}\cdot(1-\alpha_i\alpha_j)}$
S	$\frac{v_i}{c_{1i}\cdot(1-\alpha_i\alpha_j)} - \frac{f_{0i}}{f_{1i}\cdot(1-\alpha_i\alpha_j)} - \frac{\alpha_i v_j}{c_{1j}\cdot(1-\alpha_i\alpha_j)} + \frac{\alpha_j f_{0j}}{f_{1j}\cdot(1-\alpha_i\alpha_j)}$
F	$\frac{v_i+\varepsilon_i^v}{c_{1i}+\varepsilon_i^c-\alpha_j(c_{1j}+\varepsilon_j^c)} - \frac{f_{0i}+\varepsilon_i^{f_0}}{(f_{1i}+\varepsilon_i^{f_1})(1-\alpha_i\alpha_j)} - \frac{\alpha_i(v_j+\varepsilon_j^v)}{c_{1j}+\varepsilon_j^c-\alpha_i(c_{1i}+\varepsilon_i^c)} + \frac{\alpha_i(f_{0j}+\varepsilon_j^{f_0})}{(f_{1j}+\varepsilon_j^{f_1})(1-\alpha_i\alpha_j)}$
C	$\frac{(v_i+\varepsilon_i^v)(f_{1i}+\varepsilon_i^{f_1})}{(c_{1i}+\varepsilon_i^c-\alpha_j(c_{1j}+\varepsilon_j^c))f_{1i}} - \frac{f_{0i}}{f_{1i}\cdot(1-\alpha_i\alpha_j)} - \frac{\alpha_i(v_j+\varepsilon_j^v)(f_{1j}+\varepsilon_j^{f_1})}{(c_{1j}+\varepsilon_j^c-\alpha_i(c_{1i}+\varepsilon_i^c))f_{1j}} + \frac{\alpha_i f_{0j}}{f_{1j}\cdot(1-\alpha_i\alpha_j)}$
R	$\frac{v_i f_{1i}}{c_{1i}\cdot(f_{1i}+\varepsilon_i^{f_1})} - \frac{f_{0i}+\varepsilon_i^{f_0}}{(f_{1i}+\varepsilon_i^{f_1})(1-\alpha_i\alpha_j)} - \frac{\alpha_i v_j f_{1j}}{c_{1j}\cdot(f_{1j}+\varepsilon_j^{f_1})} + \frac{\alpha_i(f_{0j}+\varepsilon_j^{f_0})}{(f_{1j}+\varepsilon_j^{f_1})(1-\alpha_i\alpha_j)}$

	q_i^d	q_i^r
P	$\frac{v_i f_{1i}\cdot(1-\alpha_i\alpha_j)}{c_{1i}-\alpha_j c_{1j}}$	$\frac{v_i f_{1i}\cdot(1-\alpha_i\alpha_j)}{c_{1i}-\alpha_j c_{1j}}$
S	$\frac{v_i f_{1i}}{c_{1i}}$	$\frac{v_i f_{1i}}{c_{1i}}$
F	$\frac{(v_i+\varepsilon_i^v)\cdot(f_{1i}+\varepsilon_i^{f_1})\cdot(1-\alpha_i\alpha_j)}{c_{1i}+\varepsilon_i^c-\alpha_j(c_{1j}+\varepsilon_i^c)}$	$\frac{(v_i+\varepsilon_i^v)f_{1i}\cdot(1-\alpha_i\alpha_j)}{c_{1i}+\varepsilon_i^c-\alpha_j(c_{1j}+\varepsilon_j^c)} + \frac{f_{0i}\varepsilon_i^{f_1}-f_{1i}\varepsilon_i^{f_0}}{f_{1i}+\varepsilon_i^{f_1}}$
C	$\frac{(v_i+\varepsilon_i^v)\cdot(f_{1i}+\varepsilon_i^{f_1})\cdot(1-\alpha_i\alpha_j)}{c_{1i}+\varepsilon_i^c-\alpha_j(c_{1j}+\varepsilon_i^c)}$	$\frac{(v_i+\varepsilon_i^v)\cdot(f_{1i}+\varepsilon_i^{f_1})\cdot(1-\alpha_i\alpha_j)}{c_{1i}+\varepsilon_i^c-\alpha_j(c_{1j}+\varepsilon_i^c)}$
R	$\frac{v_i f_{1i}\cdot(1-\alpha_i\alpha_j)}{c_{1i}}$	$\frac{v_i f_{1i}^2(1-\alpha_i\alpha_j)}{c_{1i}(f_{1i}+\varepsilon_i^{f_1})} + \frac{f_{0i}\varepsilon_i^{f_1}-f_{1i}\varepsilon_i^{f_0}}{f_{1i}+\varepsilon_i^{f_1}}$

The total welfare levels achieved under the different scenarios are given by:

	W
P	$\sum_i[v_i\ln(\frac{v_i f_{1i}\cdot(1-\alpha_i\alpha_j)}{c_{1i}-\alpha_j c_{1j}}) - v_i + \frac{(c_{1i}-\alpha_j c_{1j})f_{01}}{f_{1i}\cdot(1-\alpha_i\alpha_j)} - c_{0i}]$
S	$\sum_i[v_i\ln(\frac{v_i f_{1i}}{c_{1i}}) - \frac{(c_{1i}-\alpha_j c_{1j})v_i}{c_{1i}\cdot(1-\alpha_i\alpha_j)} + \frac{(c_{1i}-\alpha_j c_{1j})f_{01}}{f_{1i}\cdot(1-\alpha_i\alpha_j)} - c_{0i}]$
F	$\sum_i[v_i\ln(\frac{(v_i+\varepsilon_i^v)f_{1i}\cdot(1-\alpha_i\alpha_j)}{c_{1i}+\varepsilon_i^c-\alpha_j(c_{1j}+\varepsilon_j^c)} + \frac{f_{0i}\varepsilon_i^{f_1}-f_{1i}\varepsilon_i^{f_0}}{f_{1i}+\varepsilon_i^{f_1}}) - \frac{(c_{1i}-\alpha_j c_{1j})(v_i+\varepsilon_i^v)}{c_{1i}+\varepsilon_i^c-\alpha_j(c_{1j}+\varepsilon_j^c)} + \frac{(c_{1i}-\alpha_j c_{1j})(f_{01}+\varepsilon_i^{f_0})}{(f_{1i}+\varepsilon_i^{f_1})(1-\alpha_i\alpha_j)} - c_{0i}]$
C	$\sum_i[v_i\ln(\frac{(v_i+\varepsilon_i^v)(f_{1i}+\varepsilon_i^{f_1})(1-\alpha_i\alpha_j)}{c_{1i}+\varepsilon_i^c-\alpha_j(c_{1j}+\varepsilon_j^c)}) - \frac{(c_{1i}-\alpha_j c_{1j})(v_i+\varepsilon_i^v)(f_{1i}+\varepsilon_i^{f_1})}{(c_{1i}+\varepsilon_i^c-\alpha_j(c_{1j}+\varepsilon_j^c))f_{1i}} + \frac{(c_{1i}-\alpha_j c_{1j})f_{01}}{f_{1i}\cdot(1-\alpha_i\alpha_j)} - c_{0i}]$
R	$\sum_i[v_i\ln(\frac{v_i f_{1i}^2(1-\alpha_i\alpha_j)}{c_{1i}(f_{1i}+\varepsilon_i^{f_1})} + \frac{f_{0i}\varepsilon_i^{f_1}-f_{1i}\varepsilon_i^{f_0}}{f_{1i}+\varepsilon_i^{f_1}}) - \frac{(c_{1i}-\alpha_j c_{1j})v_i f_{1i}}{c_{1i}\cdot(f_{1i}+\varepsilon_i^{f_1})} + \frac{(c_{1i}-\alpha_j c_{1j})(f_{01}+\varepsilon_i^{f_0})}{(f_{1i}+\varepsilon_i^{f_1})(1-\alpha_i\alpha_j)} - c_{0i}]$

One should note that the general results from the basic model presented above apply to this particular case of log utility, linear costs and linear production as well. In the absence of externalities (i.e., when $\alpha_i = \alpha_j = 0$), state control is efficient (Proposition 1). If the federal government correctly accounts for all local conditions (i.e, $\varepsilon_i^v = \varepsilon_i^c = \varepsilon_i^{f_0} = \varepsilon_i^{f_1} = 0\ \forall i$), then both federal control and conjoint federalism are efficient (Proposition 2). When there are neither externalities nor assessment errors (i.e, $\alpha_i = \varepsilon_i^v = \varepsilon_i^c = \varepsilon_i^{f_0} = \varepsilon_i^{f_1} = 0$ $\forall i$), then all decentralization scenarios are efficient (Proposition 3). If there are no errors in the federal government's assessment of either local background levels or local marginal product (i.e., $\varepsilon_i^{f_0} = \varepsilon_i^{f_1} = 0\ \forall i$), then federal control and conjoint federalism are equivalent (Proposition 4). If there are no externalities and no errors in the federal government's assessment of either local background levels or local marginal product (i.e., $\alpha_i = \varepsilon_i^{f_0} = \varepsilon_i^{f_1} = 0\ \forall i$), then reverse conjoint federalism is efficient (Proposition 5).

In addition to confirming the general propositions presented earlier, this special case of log utility, linear costs and linear production also yields two additional results:

1. The constants c_{0i} and c_{0j} in the cost functions have no effect on the ordinal ranking of the welfares arising from the different decentralization scenarios; they serve merely to shift all welfare values. This is because total costs, and therefore the constant component of total costs, enter linearly in the social welfare function.

2. The constants f_{0i} and f_{0j} in the production functions only affect the ordinal ranking of the welfares arising from the different scenarios through terms that also include the errors $\varepsilon_i^{f_1}$ and $\varepsilon_j^{f_1}$ in assessing the respective state's marginal product. That is, for each state i, if there is no error $\varepsilon_i^{f_1}$, then the ranking of the welfares of the different scenarios is invariant to the constant f_{0i}. As explained above, this constant can be interpreted as the background level of environmental quality; that is, the level of environmental quality that would arise in the absence of anthropogenic effort.

4.2 Results for symmetric version

To gain further intuition for how the second-best decentralization scenario depends on the various parameters, I consider a the special case of log utility, linear costs and linear technology in which the two states are entirely symmetric. That is, $v_i = v_j$, $c_{0i} = c_{0j}$, $c_{1i} = c_{1j}$, $f_{0i} = f_{0j}$, $f_{1i} = f_{1j}$, $\alpha_i = \alpha_j$, $\varepsilon_i^v = \varepsilon_j^v$, $\varepsilon_i^c = \varepsilon_j^c$, $\varepsilon_i^{f_0} = \varepsilon_j^{f_0}$, and $\varepsilon_i^{f_1} = \varepsilon_j^{f_1}$. I restrict myself to parameter values that make the welfare arising from the social planner's solution non-negative[10] and that make the effort levels chosen under all scenarios non-negative.[11] The qualitative features of the results are robust to the actual choices of the parameter values,

[10] For each state i, assuming that $c_{1i} > 0$, $f_{1i} > 0$ and $\alpha_i > -1$, the welfare from the social planner's problem is non-negative if and only if

$$f_{0i} \geq (1+\alpha_i) f_{1i} \frac{v_i}{c_{1i}} (1 + \frac{c_{0i}}{v_i} - \ln((1+\alpha_i) f_{1i} \frac{v_i}{c_{1i}}))$$

I also check to make sure that the welfare arising from the social planner's solution is at least as large as those arising from all other decentralization scenarios.

[11] For each state i, assuming that $c_{1i} > 0$, $c_{1i} + \varepsilon_i^c > 0$, $f_{1i} > 0$, $f_{1i} + \varepsilon_i^f > 0$, and $\alpha_i > -1$, the effort levels chosen by the social planner are non-negative if and only if

$$f_{0i} \leq \frac{v_i f_{1i}}{c_{1i}}$$

The effort levels chosen under federal control are non-negative if and only if

$$f_{0i} + \varepsilon_i^{f_0} \leq \frac{(1+\alpha_i)(v_i + \varepsilon_i^v)(f_{1i} + \varepsilon_i^f)}{c_{1i} + \varepsilon_i^c}$$

The effort levels chosen under conjoint federalism are non-negative if and only if provided that they meet these two sets of constraints.[12] In particular, without loss of generality, I set the constant in the cost equation to zero: $c_{0i} = c_{oj} = 0$. As explained above, this constant serves merely to shift all welfare values; it does not affect relative welfares. I also set $v_i = v_j = 60$, $c_{1i} = c_{1j} = 1$, $f_{0i} = f_{0j} = 1$, and $f_{1i} = f_{1j} = 10$. To address errors in rounding, welfare values in the simulation are considered equal if they are within 1×10^{-7} of each other.

For each of the four local conditions (benefit, cost, background, and marginal product), I plot the second-best scenario as a function of the externality α_i and of the error in the federal government's assessment of that condition, setting the errors in the federal government's assessment of the other three local conditions to zero. All four plots share general features that confirm the general analytic results presented above:

1. In the absence of externalities (i.e., when $\alpha_i = \alpha_j = 0$), state control is efficient (Proposition 1).
2. Both federal control and conjoint federalism are efficient when the particular assessment error being anlyzed is set to zero. Since all other assessment errors are already set at zero, Proposition 2 applies.
3. When both the externality and the particular error being analyzed equal zero, all decentralization scenarios are efficient. Since all other assessment errors are already set at zero, Proposition 3 applies.

I now examine each individual plot in detail.

4.2.1 α vs. ε^v

Figure 1 shows the second-best decentralization scenario as a function of externality $\alpha_i = \alpha_j$ and the federal government's error $\varepsilon_i^v = \varepsilon_j^v$ in assessing local benefits, assuming no other error in the federal government's assessments. I vary the externality α_i from -1 to 1 and the error ε_i^v from $-\frac{3}{4}v_i$ to $\frac{7}{4}v_i$.[13]

$$f_{0i} \leq \frac{(1+\alpha_i)(v_i+\varepsilon_i^v)(f_{1i}+\varepsilon_i^f)}{c_{1i}+\varepsilon_i^c}$$

The effort levels under reverse conjoint federalism are non-negative if and only if

$$f_{0i}+\varepsilon_i^{f_0} \leq \frac{(1-\alpha_i^2)v_i f_{1i}}{c_{1i}}.$$

[12] In fact, the qualitative results from the graphs comparing the externality with either the error in benefit assessment, that in cost assessment, or that in background assessment are robust to the choices of the parameters even if they do not satisfy the constraints imposed by requiring the welfare at the social optimum and all effort choices to be non-negative. The constraints only affect the qualitative results for the graphs which compare the externality with the marginal product assessment error.

[13] A lower bound of $-\frac{3}{4}v_i$ ensures that the assessed benefits, $V_{F,i} = (v_i+\varepsilon_i^v)\ln(q_i)$, is positive.

For each pair $(\alpha_i, \varepsilon_i^v)$ of parameter values, the letters "S", "F", "C", and "R" denote whether state control, federal control, conjoint federalism, or reverse conjoint federalism, respectively, is the second-best scenario. When more than one scenario achieves the second-best, the letters appear smaller and are joined by an $\otimes$. If the second-best scenario also achieves the first best, the letter is in bold.

In addition to the general features mentioned above that Figure 1 shares with the other graphs in this section, the following specific results arise when the federal government only errs in assessing local benefits:

1. Federal control is equivalent to conjoint federalism. This is because errors in the federal government's assessment of local background and of local technology, the only sources of differences between the two scenarios, are assumed to be nonexistent. Proposition 4 therefore applies.

2. When there is no externality ($\alpha_i = 0$), reverse conjoint federalism, like state control, achieves the first best. Reverse conjoint federalism is efficient in this case as well since, as noted above, the only inefficiencies that arise in this form of delegation are those from the externality and from the federal government's errors in assessing local background and local marginal product. Since these two errors are assumed to be zero for this figure, reverse conjoint federalism is efficient whenever the externality is also zero.

3. Federal control and conjoint federalism are second best when the absolute value of the externality is large and the absolute value of the benefit assessment error is small. There is a tradeoff between externalities on the one hand and benefit assessment error on the other. That is, all else equal, as the benefit assessment error increases in magnitude, a higher magnitude in externality is needed before conjoint federalism (or, equivalently, federal control) becomes more efficient than both state control and reverse conjoint federalism.

4. Reverse conjoint federalism dominates state control when the externality is negative. Mathematically, for a given magnitude of the externality, the sign of the externality does not affect the output choice but does affect the effort choice. In particular, the difference in effort choice between state control and reverse conjoint federalism in a symmetric model when $\varepsilon_i^{f_0} = \varepsilon_i^{f_1} = 0$,

$$a_i^S - a_i^R = \frac{\alpha_i^2 v_i}{(1+\alpha_i)\, c_{1i}},$$

is smaller under $\alpha_i = \alpha_0 > 0$ than it is under $\alpha_i = -\alpha_0$. Thus, for a given magnitude in the externality, even though the output choice, and hence the difference in the output choices under the two scenarios, is the same regardless of the sign of the externality, the relative difference in effort between state control and reverse conjoint federalism needed to implement the same outputs is higher when the externality is negative. Thus, for a given magnitude of the externality, effort cost is higher under state control relative to reverse conjoint federalism when the externality is negative. Thus, reverse conjoint federalism is more efficient than state control when the externality is negative.

Thus, when the federal government's only assessment error is that of local benefits, then, all else equal, federal control and conjoint federalism are second best when there are large externalities and small benefit assessment errors; state control is second best when there are small positive externalities and large benefit assessment errors; and reverse conjoint federalism is second best when there are small negative externalities and large benefit assessment errors.

4.2.2 α vs. ε^c

Figure 2 shows the second-best decentralization scenario as a function of externality $\alpha_i = \alpha_j$ and the federal government's error $\varepsilon_i^c = \varepsilon_j^c$ in assessing local costs, assuming no other error in the federal government's assessments. I vary the externality α_i from -1 to 1 and the error ε_i^c from $-\frac{3}{4}c_{1i}$ to $\frac{7}{4}c_{1i}$. For each pair $(\alpha_i, \varepsilon_i^c)$ of parameter values, the letters "S", "F", "C", and "R" denote whether state control, federal control, conjoint federalism, or reverse conjoint federalism, respectively, is the second-best scenario. When more than one scenario achieves the second-best, the letters appear smaller and are joined by an $\otimes$. If the second-best scenario also achieves the first best, the letter is in bold.

The most striking feature of Figure 2 is that, qualitatively, it is almost exactly like Figure 1, except with a rescaling of the x-axis. That is, the ranges of $(\alpha_i, \varepsilon_i^c)$ pairs for which each scenario is second best when the federal government only errs in assessing costs are directly analogous to the ranges of $(\alpha_i, \varepsilon_i^v)$ pairs for which each scenario is second best when the federal government only errs in assessing benefits. For any given value of the externality, the scenario that is second best at a particular value for the benefit assessment error is the same scenario that is second best at an appropriate rescaling of the cost assessment error. Intuitively, this is because both the benefit assessment error and the cost assessment error enter linearly into the federal government's objective function.

More specifically, the results that arise when the federal government only errs in assessing local costs are:

1. Federal control is equivalent to conjoint federalism. This is true for the same reasoning given in the analysis of the analogous result of Figure 1, when the federal government only errs in assessing benefits, not costs.

2. When there is no externality ($\alpha_i = 0$), reverse conjoint federalism, like state control, achieves the first best. This is true for the same reasoning given in the analysis of the analogous result of Figure 1.

3. Federal control and conjoint federalism are second best when the absolute value of the externality is large and the absolute value of the cost assessment error is small. There is a tradeoff between externalities on the one hand and cost assessment error on the other. That is, all else equal, as the cost assessment error increases in magnitude, a higher magnitude in externality is needed before conjoint federalism (or, equivalently, federal control) becomes more efficient than both state control and reverse conjoint federalism.

4. Reverse conjoint federalism dominates state control when the externality is negative. This is true for the same reasoning given in the analysis of the analogous result of Figure 1.

Thus, when the federal government's only assessment error is that of local costs, then, all else equal, federal control and conjoint federalism are second best when there are large externalities and small cost assessment errors; state control is second best when there are small positive externalities and large cost assessment errors; and reverse conjoint federalism is second best when there are small negative externalities and large cost assessment errors.

4.2.3 α vs. ε^{f_0}

Figure 3 shows the second-best decentralization scenario as a function of externality $\alpha_i = \alpha_j$ and the federal government's error $\varepsilon_i^{f_0} = \varepsilon_j^{f_0}$ in assessing local background levels of environmental quality, assuming no other error in the federal government's assessments. I vary the externality α_i from -1 to 1 and the error $\varepsilon_i^{f_0}$ from $-\frac{5}{6}|f_{0i}|$ to $\frac{5}{6}|f_{0i}|$. As before, for each pair $(\alpha_i, \varepsilon_i^{f_0})$ of parameter values, the letters "S", "F", "C", and "R" denote whether state control, federal control, conjoint federalism, or reverse conjoint federalism, respectively, is the second-best scenario. When more than one scenario achieves the second-best, the letters appear smaller and are joined by an $\otimes$. If the second-best scenario also achieves the first best, the letter is in bold.

The figure presents the following specific results that arise when the federal government only errs in assessing local background:

1. When there is no background assessment error ($\varepsilon_i^{f_0} = 0$), federal control is equivalent to conjoint federalism. Since the only other source of differences between the two scenarios–the marginal product assessment error $\varepsilon_i^{f_1}$–is assumed to be nonexistent, Proposition 4 applies.

2. Conjoint federalism is always first best efficient. This is because all the sources of inefficiency in this scenario–errors in assessing benefits, costs and marginal product–are assumed to be nonexistent. The existence of background assessment errors does not introduce any inefficiencies in conjoint federalism. The intuition is as follows. Because the federal

government's choice of output comes from a first-order condition equating marginal benefits with marginal costs, the error in assessing the background (or, equivalently, the constant in the production function) does not affect the federal government's choice of output. If no other errors exist, then the federal government's choice of output is efficient. However, while background assessment errors do not affect the federal government's choice of output, they do affect its choice of effort given output. In conjoint federalism, however, the effort choice is left up to the states; as a consequence, effort levels are efficient as well.

Thus, when the federal government's only assessment error is that of local background environmental quality levels, then conjoint federalism is always first best; state control is first best when there is no externality; federal control is first best when there is no background assessment error; and all scenarios are first best when there are neither externalities nor background assessment errors.

4.2.4 α vs. ε^{f_1}

Figure 4 shows the second-best decentralization scenario as a function of externality $\alpha_i = \alpha_j$ and the federal government's error $\varepsilon_i^{f_1} = \varepsilon_j^{f_1}$ in assessing local marginal product, assuming no other error in the federal government's assessments. Because the constant f_{0i} in the production function affects the ordinal ranking of the different scenarios once the federal government errs in assessing local marginal product, Figures 5 and 6 show the analogous results when the constant f_{0i} in the production function is assumed to be zero and negative one, respectively, instead of positive one. I vary the externality α_i from -1 to 1 and the error $\varepsilon_i^{f_1}$ from $-\frac{5}{6}f_{1i}$ to $\frac{5}{6}f_{1i}$.[14] As before, for each pair $(\alpha_i, \varepsilon_i^{f_1})$ of parameter values, the letters "S", "F", "C", and "R" denote whether state control, federal control, conjoint federalism, or reverse conjoint federalism, respectively, is the second-best scenario. When more than one scenario achieves the second-best, the letters appear smaller and are joined by an $\otimes$. If the second-best scenario also achieves the first best, the letter is in bold.

The figure presents the following specific results that arise when the federal government only errs in assessing local marginal product:

1. When there is no marginal product assessment error ($\varepsilon_i^{f_1} = 0$), federal control is equivalent to conjoint federalism. Since the only other source of differences between the two scenarios–the background assessment error $\varepsilon_i^{f_0}$–is assumed to be nonexistent, Proposition 4 applies.

[14] For each of the three values for the constant f_{0i}, and for each value of the error $\varepsilon_i^{f_1}$, all the parameters still satisfy the constraints imposed by requiring welfare at the social optimum and all effort choices to be non-negative.

2. Federal control is first best when the background level of environmental quality output is zero (i.e., $f_{0i} = 0$). This is because the marginal product assessment error $\varepsilon_i^{f_1}$ only affects the welfare under federal control through terms that are multiplied by either the background level f_{0i} or the federal government's error $\varepsilon_i^{f_0}$ in assessing it. Thus, since the latter is assumed zero, if the former is zero as well, then all the terms that include the error $\varepsilon_i^{f_1}$ drop out; the error no longer introduces any inefficiencies. Since all other errors are assumed nonexistent, federal control achieves the social optimum.

3. When the background f_{0i} is nonzero, federal control is at least second best as long as the externality is nonzero. As explained above, state control is clearly first best when the externality is equal to zero. When the externality is nonzero, however, federal control achieves the second best tradeoff between internalizing externalities and incorrectly assessing local marginal product.

Thus, when the federal government's only assessment error is that of local marginal productivity of effective effort, then federal control is generally at least second best unless the externality is nonzero; state control is first best when the externality is zero; federal control is first best when there is no marginal product assessment error; and all scenarios are first best when there are neither externalities nor marginal product assessment errors.

4.2.5 Comparing the decentralization scenarios

The results from Figures 1-6 can be used to summarize the conditions under which the various decentralization scenarios are second best efficient.

In general, state control should be used when:

- there are no externalities, or
- externalities are small and positive, and benefit or cost assessment errors are large

In general, federal control should be used when:

- there are no assessment errors
- externalities are large, benefit assessment errors are small, and all other assessment errors are nonexistent
- externalities are large, cost assessment errors are small, and all other assessment errors are nonexistent, or
- externalities are nonzero and the only assessment error is that of marginal product

In general, conjoint federalism should be used when:

- there are no assessment errors
- externalities are large, benefit assessment errors are small, and all other assessment errors are nonexistent
- externalities are large, cost assessment errors are small, and all other assessment errors are nonexistent, or
- the only assessment error is that of local background

In general, reverse conjoint federalism should be used when:

- there are neither externalities and nor assessment errors in either local background or local marginal product, or
- externalities are small and negative, either benefit or cost assessment errors are large, and no other assessment errors exist

4.2.6 Comparing the four types of assessment error

Suppose that externalities were present and that the federal government committed only one type of assessment error. Assuming that the optimal decentralization scenario were chosen, would it be possible to determine which error was committed based on information about the scenario choice alone? In other words, would the observed choice of decentralization scenario enable one to empirically distinguish among the different assessment errors?

Unfortunately, the answer is "no". One problem is that the profile of second-best optimal decentralization choices produced by benefit assessment errors and by cost assessment errors are observationally equivalent. The other problem is that each scenario may be second best under any of the errors, depending on the values of both the externality and the error.

However, were one to observe multiple choices of decentralization scenarios, with each choice resulting from a tradeoff between externalities and the same type of assessment error but from different values of the externality and error, then one might be able to use the distribution of the scenarios chosen to distinguish among the different types of error, even if the actual values of the externality and error were unobeserved, provided that these values spanned a large enough range. If all different scenarios were chosen at least once, then the assessment error was likely in either benefit or cost. If only conjoint federalism was chosen, the assessment error was likely in background levels. If only federal control was chosen, the assessment error was likely in marginal product. These results suggest possible avenues for empirical research.

5 Concluding remarks

In this paper I examine the optimal degree of decentralization for environmental regulation when the tradeoff is between the federal government's ability to internalize externalities on the one hand and its inability to correctly assess local benefits, costs, and/or production technology on the other. I provide a basic model that is useful both as a framework for characterizing the tradeoffs involved in the general issue of environmental federalism and as a tool for determining the optimal decentralization scenario for any particular environmental problem at hand. My results show that the second best choice of decentralization scenario depends on the extent of the externality and of the misassessment, and that, under certain values of the parameters, a form of partial decentralizaiton may be the most efficient. For the special case of log utility, linear costs, linear production, and symmetric states, conjoint federalism–the particular form of delegation used for ozone smog regulation in the United States–is second best when externalities are large and the federal governmental errs only slightly in assessing local benefits or costs but does not err in assessing any other local condition; or when the federal government only errs in assessing local background environmental quality levels. My results for this special case also show that, under certain values of the parameters, a reverse form of delgation may be second best, particularly if externalities are small and negative[15] and the federal government errs greatly in assessing local benefits or costs but not in anything else. In future work, I hope to apply my model to ozone smog regulation to examine whether the actual choice of conjoint federalism in the U.S. is also the second-best optimal one. 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.

[15] Such negative externalities in pollution control effort may arise if one state's pollution levels are abated by transporting the pollutant to another state. For instance, air pollution in one state may be reduced by building taller smokestacks so that the pollutant is blown to another state before it settles. Similarly, solid waste may be reduced in one state by simply dumping the trash in other state's landfill.

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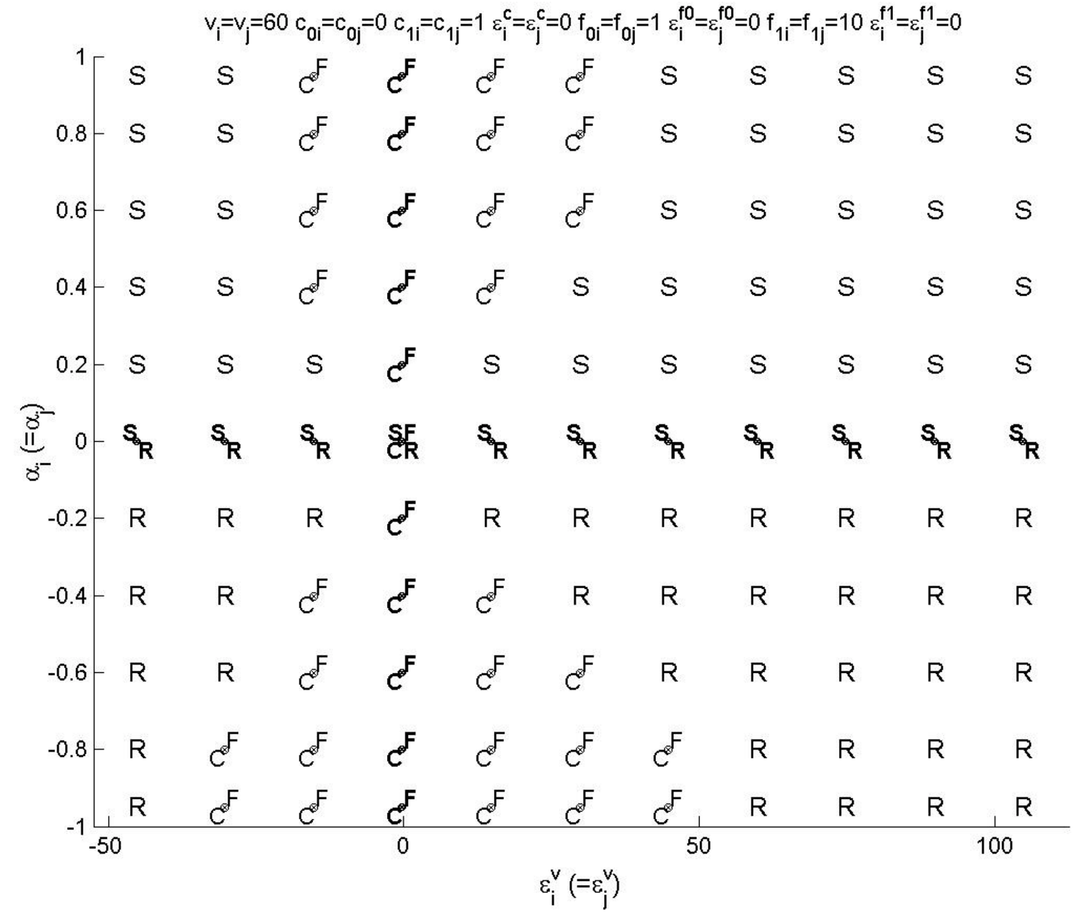

Figure 1: The second-best decentralization scenario as a function of externality $\alpha_i = \alpha_j$ and the federal government's error $\varepsilon_i^v = \varepsilon_j^v$ in assessing local benefits, assuming no other error in the federal government's assessments. For each pair $(\alpha_i, \varepsilon_i^v)$ of parameter values, the letters "S", "F", "C", and "R" denote whether state control, federal control, conjoint federalism, or reverse conjoint federalism, respectively, is the second-best scenario. When more than one scenario achieves the second-best, the letters appear smaller and are joined by an $\otimes$. If the second-best scenario also achieves the first best, the letter is in bold.

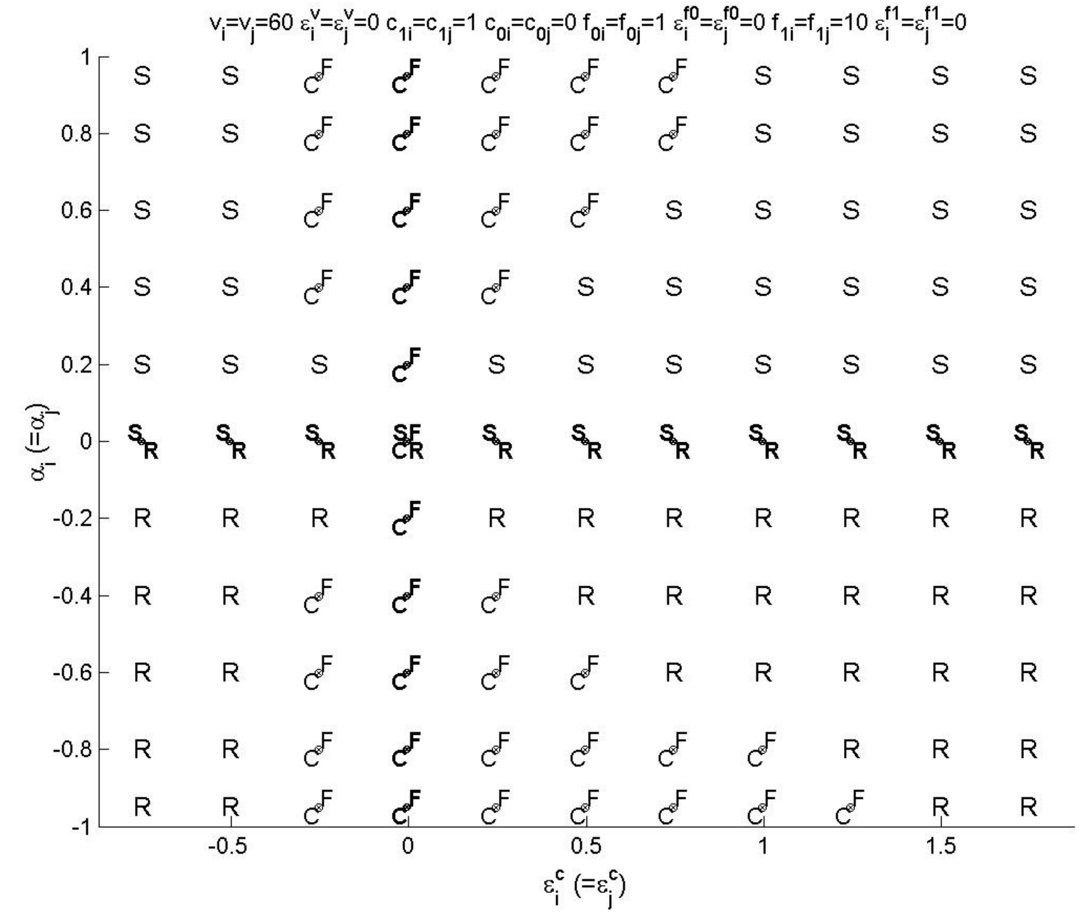

Figure 2: The second-best decentralization scenario as a function of externality $\alpha_i = \alpha_j$ and the federal government's error $\varepsilon_i^c = \varepsilon_j^c$ in assessing local costs, assuming no other error in the federal government's assessments. For each pair $(\alpha_i, \varepsilon_i^c)$ of parameter values, the letters "S", "F", "C", and "R" denote whether state control, federal control, conjoint federalism, or reverse conjoint federalism, respectively, is the second-best scenario. When more than one scenario achieves the second-best, the letters appear smaller and are joined by an $\otimes$. If the second-best scenario also achieves the first best, the letter is in bold.

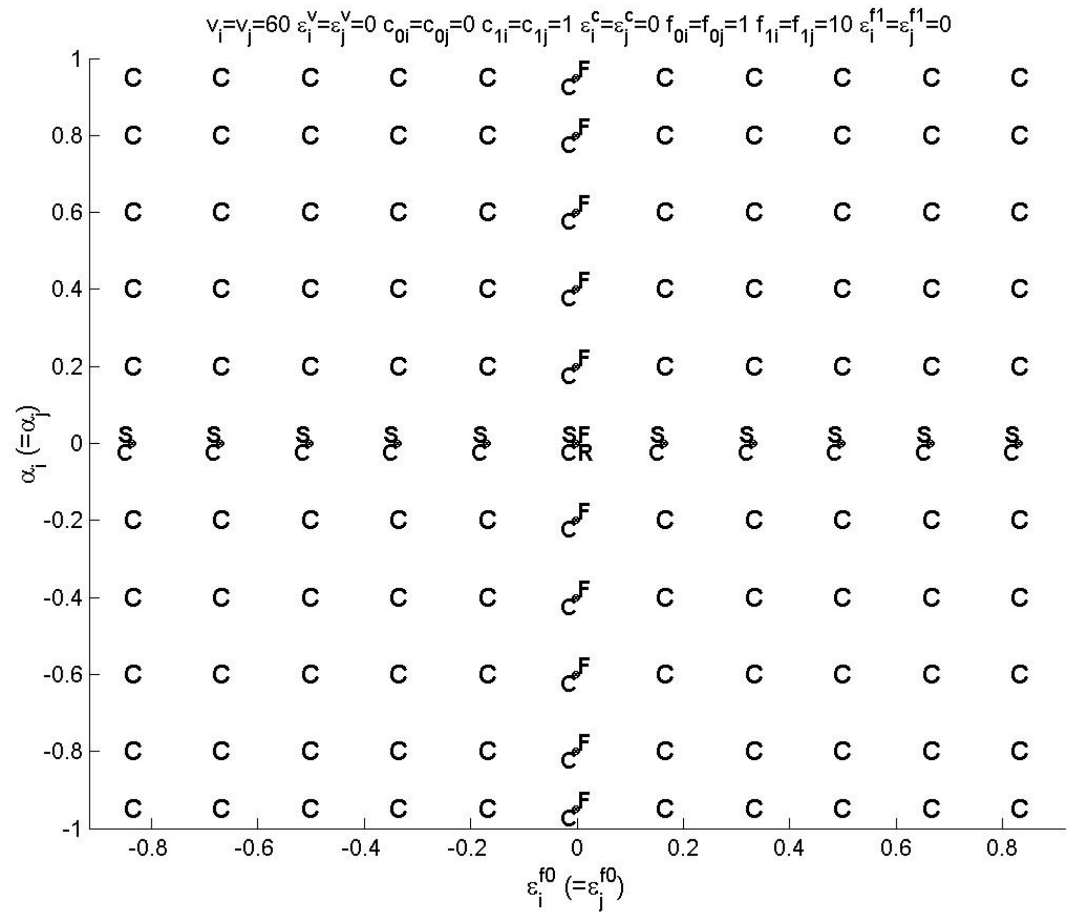

Figure 3: The second-best decentralization scenario as a function of externality $\alpha_i = \alpha_j$ and the federal government's error $\varepsilon_i^{f_0} = \varepsilon_j^{f_0}$ in assessing local background levels of environmental quality, assuming no other error in the federal government's assessments. For each pair $(\alpha_i, \varepsilon_i^{f_0})$ of parameter values, the letters "S", "F", "C", and "R" denote whether state control, federal control, conjoint federalism, or reverse conjoint federalism, respectively, is the second-best scenario. When more than one scenario achieves the second-best, the letters appear smaller and are joined by an $\otimes$. If the second-best scenario also achieves the first best, the letter is in bold.

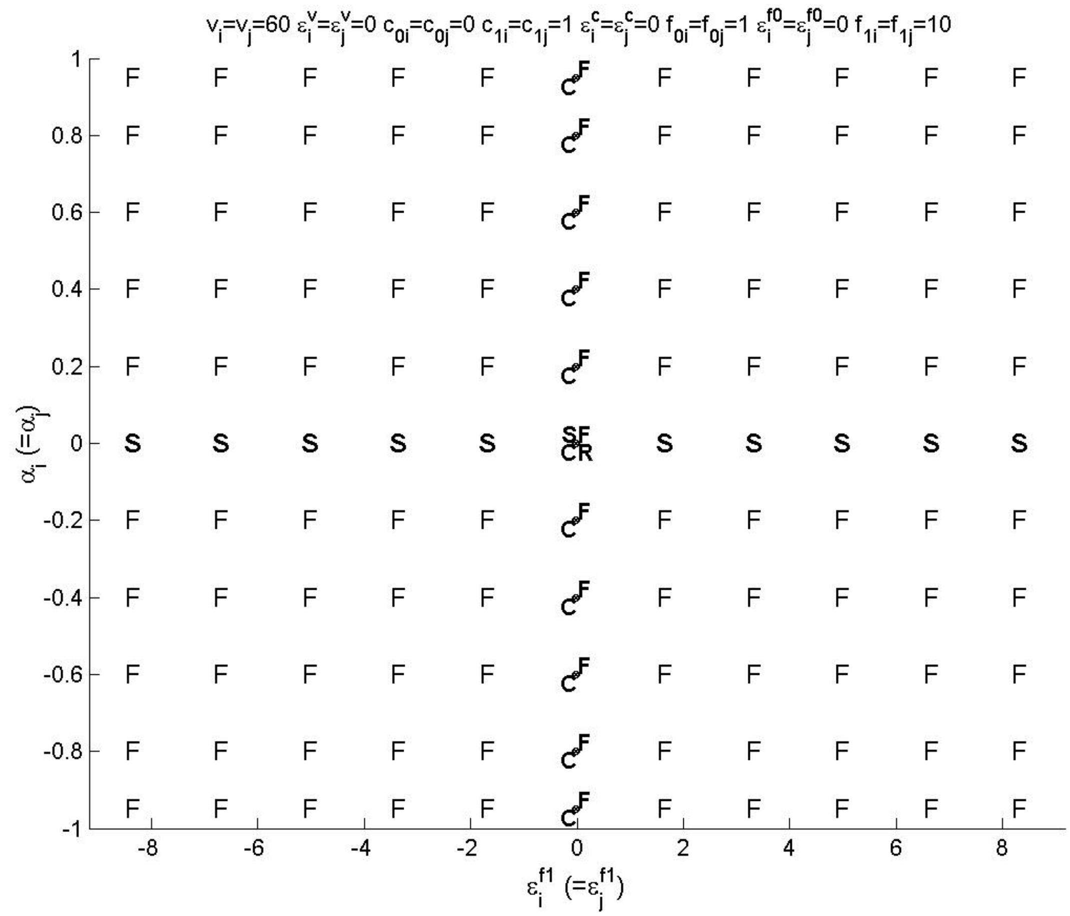

Figure 4: The second-best decentralization scenario as a function of externality $\alpha_i = \alpha_j$ and the federal government's error $\varepsilon_i^{f_1} = \varepsilon_j^{f_1}$ in assessing local marginal product, assuming no other error in the federal government's assessments. The constant f_{0i} in the production function is set at positive one. For each pair $(\alpha_i, \varepsilon_i^{f_1})$ of parameter values, the letters "S", "F", "C", and "R" denote whether state control, federal control, conjoint federalism, or reverse conjoint federalism, respectively, is the second-best scenario. When more than one scenario achieves the second-best, the letters appear smaller and are joined by an $\otimes$. If the second-best scenario also achieves the first best, the letter is in bold.

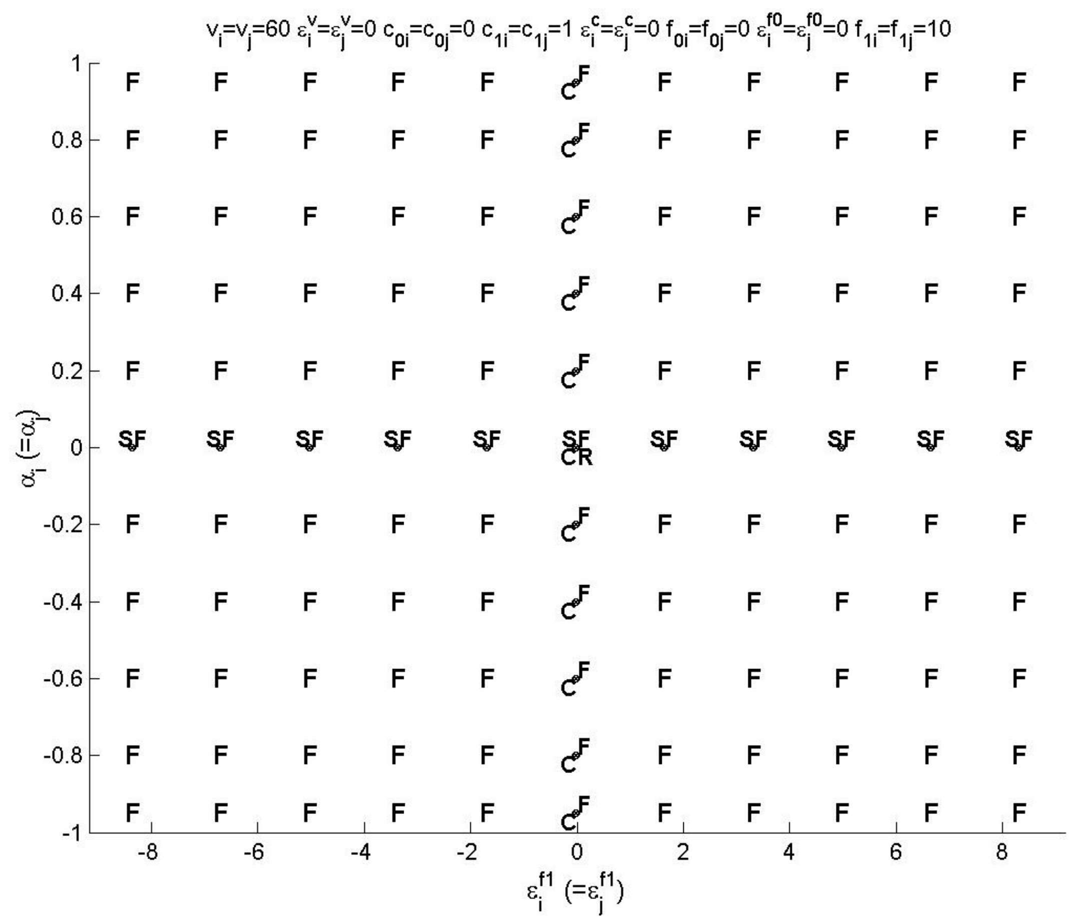

Figure 5: The second-best decentralization scenario as a function of externality $\alpha_i = \alpha_j$ and the federal government's error $\varepsilon_i^{f_1} = \varepsilon_j^{f_1}$ in assessing local marginal product, assuming no other error in the federal government's assessments. The constant f_{0i} in the production function is set at zero. For each pair $(\alpha_i, \varepsilon_i^{f_1})$ of parameter values, the letters "S", "F", "C", and "R" denote whether state control, federal control, conjoint federalism, or reverse conjoint federalism, respectively, is the second-best scenario. When more than one scenario achieves the second-best, the letters appear smaller and are joined by an $\otimes$. If the second-best scenario also achieves the first best, the letter is in bold.

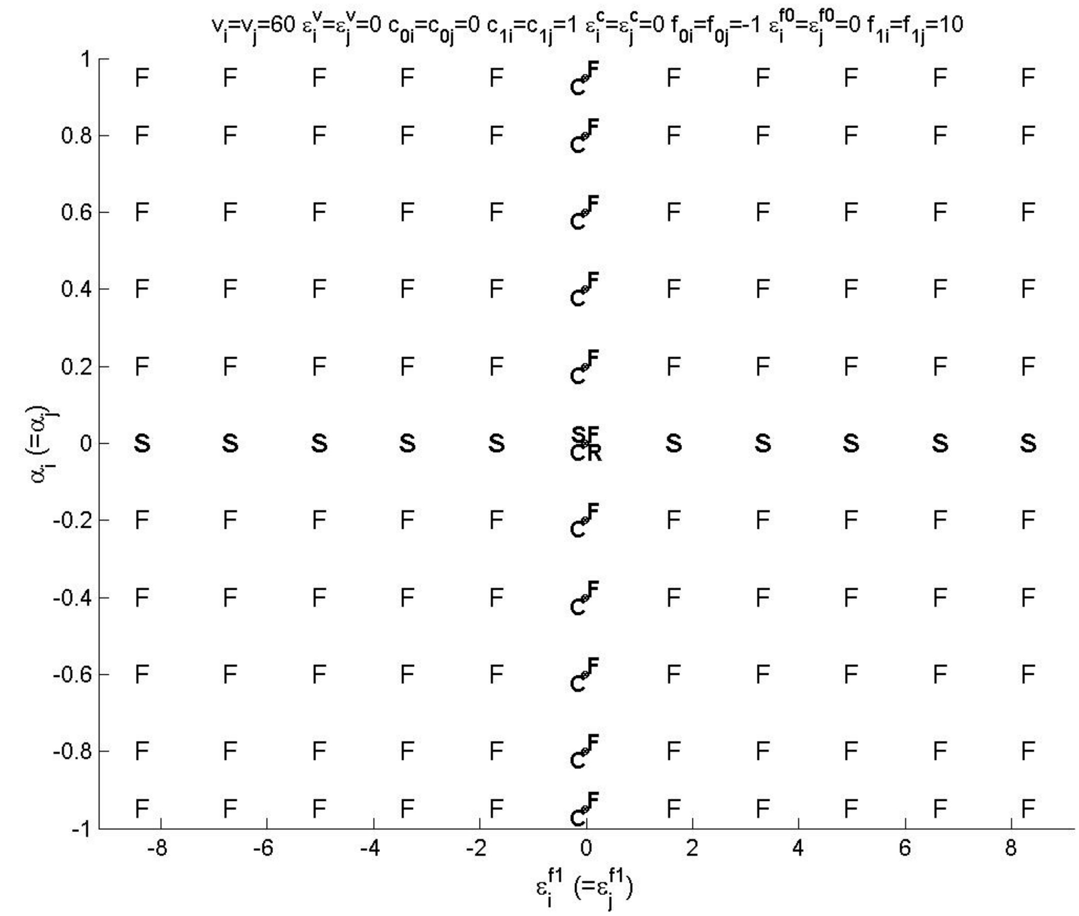

Figure 6: The second-best decentralization scenario as a function of externality $\alpha_i = \alpha_j$ and the federal government's error $\varepsilon_i^{f_1} = \varepsilon_j^{f_1}$ in assessing local marginal product, assuming no other error in the federal government's assessments. The constant f_{0i} in the production function is set at negative one. For each pair $(\alpha_i, \varepsilon_i^{f_1})$ of parameter values, the letters "S", "F", "C", and "R" denote whether state control, federal control, conjoint federalism, or reverse conjoint federalism, respectively, is the second-best scenario. When more than one scenario achieves the second-best, the letters appear smaller and are joined by an $\otimes$. If the second-best scenario also achieves the first best, the letter is in bold.