Supporting Information. Sanchirico, J.N., J.C. Blackwood, B. Fitzpatrick, D.M. Kling, S. Lenhart, M.G. Neubert, K. Shea, C.B. Sims, and M.R. Springborn. 2020. Political economy of renewable resource federalism. Ecological Applications.

Appendix S1

This supplementary appendix is structured as follows. Section one provides additional details about the bioeconomic model. Section two describes the numerical solution method. Section three illustrates the calculation for the value of switching regimes. Section four presents the baseline parameters for the analysis. Section five introduces supplementary figures associated with the analysis of the main paper. The final section includes sensitivity analyses. Sample matlab code can be found at DOI: 10.5281/zenodo.4034965.

Contents

S1 Bioeconomic Model

We model management of a spatially-connected fishery. The dynamics of fish stock biomass $x_i(t)$ in the jurisdiction of state i is given by:

$$\begin{aligned}\frac{\mathrm{d}x_i(t)}{\mathrm{d}t} &= F_i(x_i(t), x_j(t), E_i(t)) &\text{(S1)}\\ &\equiv r_i x_i(t)\left(1 - \frac{x_i(t)}{K_i}\right) - d\left(x_i(t) - x_j(t)\right) - q_i x_i(t) E_i(t) &\text{(S2)}\end{aligned}$$

Here $E_i(t)$ is fishing effort in state i, an input to a conventional harvest rate function, and $x_j(t)$ is the current stock in state j's jurisdiction. Parameters r_i and K_i govern local productivity of the stock, while d determines the per-capita rate of dispersal (per-capita emigration from state i and per-capita inflow from state j). Parameters in Eq. (S1) and in other parts of the model are defined along with their base case values in Table S1.

The economic value of fishing is determined by the rate of profit generation, which for state i are defined as:

$$\pi_i(x_i(t), E_i(t)) = \left(p_i q_i x_i(t) - [c_{i1} + c_{i2} E_i(t)]\right) E_i(t) \qquad \text{(S3)}$$

We specify constant parameters for the landings price (p_i), catchability coefficient (q_i), and cost parameters (c_{i1} and c_{i2}). While these are assumed to be fixed quantities in the model, we perform several sensitivity analyses by changing the value and re-analyzing the solution.

Different federalism institutions determine objectives for the spatial fishery, which in turn determine the spatial dynamics of the stocks and fishing effort. We develop the mathematical structure of these cases below using optimal control theory (1). For each model, we provide necessary conditions for an interior solution. None of the model variants produce intuitive analytical expressions for the open-loop optimal paths or steady states. This property of the model motivates our use of numerical methods, which we describe below. However, comparing the necessary conditions for a solution across federalism alternatives does provide insight into how the corresponding solutions differ. We emphasize these differences in what follows.

S1.1 Federal management: first best

The first-best optimal solution occurs when the federal manager is free to choose different rates of fishing effort in each state in each period to maximize the total value of the fishery over time (2). The federal manager's problem is:

$$\max_{E_1(t),E_2(t)} J_1(E_1(t)) + J_2(E_2(t)) = \max_{E_1(t),E_2(t)} \int_0^\infty [\pi_1(x_1(t), E_1(t)) + \pi_2(x_2(t), E_2(t))] e^{-\delta t} \mathrm{d}t \tag{S4}$$

subject to stock dynamics (Eq. (S1)), initial conditions (x_{10}, x_{20}), and a non-negativity constraint on $E_i(t)$. Here $J_i(t)$ measures the net present value of the aggregate state-level profits as defined in the main text.

In what follows, we emphasize the simplest form of the necessary conditions by assuming an interior solution. The current-valued Hamiltonian for the problem is then:

$$H^B(x_1(t), x_2(t), \lambda_1^B(t), \lambda_2^B(t), E(t)) = \sum_{i=1}^{2} \pi_i(x_i(t), E_i(t)) + \lambda_i^B(t) F_i(x_1(t), x_2(t), E_i(t)) \tag{S5}$$

We use the superscript "B" to differentiate the Hamiltonian and current-valued costate variables λ_i^B from those involved in the models associated with other federalism alternatives below. The first order necessary conditions (FONCs) for the problem are:

$$\frac{\partial \pi_i}{\partial E_i(t)} + \lambda_i^B(t) \frac{\partial F_i}{\partial E_i(t)} = 0, \tag{S6}$$

and

$$\dot{\lambda}_i^B(t) = \lambda_i^B(t) \left(\delta - \frac{\partial F_i}{\partial x_i(t)} \right) - \frac{\partial F_j}{\partial x_i(t)} - \frac{\pi_i}{\partial x_i(t)} \tag{S7}$$

Substituting Eqs. (S1) and (S3) into Eq. (S6) produces:

$$E_i^B = \varepsilon_i^B(x_i(t), \lambda_i^B(t)) = \frac{(p_i - \lambda_i^B(t)) q_i x_i(t) - c_{i1}}{2c_{i2}} \tag{S8}$$

Because the properties of the model is well-understood from prior work (2; 3) we do not elaborate further. We do highlight, however, that the control rule for effort in this case (Eq. (S8)) is a function of parameters, the current stock level in state i, and the current shadow value of the state i stock.

S1.2 Federal management: command-and-control

Under federal command-and-control management, the federal manager enforces equal fishing effort $E(t)$ in each state ($E_1(t) = E_2(t) = E(t)\ \forall t$. The objective of the uniform effort policy is to maximize the sum of discounted net present value of fishing profits across states:

$$\max_{E(t)} J^C(E(t)) = \max_{E(t)} \int_0^\infty \left[\pi_1(x_1(t), E(t)) + \pi_2(x_2(t), E(t))\right] e^{-\delta t} \mathrm{d}t \tag{S9}$$

subject to stock dynamics (Eq. (S1)), initial conditions (x_{10}, x_{20}), and a non-negativity constraint on $E(t)$. We assume an interior solution exists and consider the current-value Hamiltonian for this problem:

$$\begin{aligned} &H^C(x_1(t), x_2(t), \lambda_1^C(t), \lambda_2^C(t), E(t)) = \\ &\qquad \sum_{i=1}^{2} \pi_i(x_i(t), E(t)) + \lambda_i^C(t) F_i(x_1(t), x_2(t), E(t)) \end{aligned} \tag{S10}$$

Along with the stock dynamics, the first order necessary conditions are:

$$\sum_{i=1}^{2} \frac{\partial \pi_i}{\partial E(t)} + \lambda_i^C(t) \frac{\partial F_i}{\partial E(t)} = 0 \tag{S11}$$

$$\dot{\lambda}_i^C(t) = \lambda_i^C(t)\left(\delta - \frac{\partial F_i}{\partial x_i(t)}\right) - \frac{\partial F_j}{\partial x_i(t)} - \frac{\pi_i}{\partial x_i(t)} \tag{S12}$$

Eq. (S11) may be rearranged to form a necessary relationship between uniform effort and the states and shadow values:

$$E(t) = \varepsilon_C(x_1(t), x_2(t), \lambda_1^C(t), \lambda_2^C(t)) = \frac{\sum_{i=1}^{2} (p_i - \lambda_i^C) q_i x_i(t) - c_{i1}}{2(c_{12} + c_{22})} \tag{S13}$$

Contrasting Eqs. (S8) and (S13) reveals how the uniform effort level responds to information about the value of the stocks in both states. The rate of fishing effort is determined in part by a weighted average of shadow values. In particular, the rate of fishing effort may be higher or lower than what would be applied under first-best management. Another important point is that $\lambda_i^B(t)$ and $\lambda_i^C(t)$ will in general not be equal at t given that they are endogenous to the dynamics induced by the different effort choices and governance regims.

S1.3 Federal management: market-based policy

The federal manager imposes a market-based policy by establishing a fishing quota market that encompasses the two state-level fisheries with one to one trading of quota between the states. In the first-best policy, the quota market price per unit in each period is $\lambda_i^B(t)$, which corresponds to the marginal value (shadow price) of another unit of fish stock in that state (2). If we were to open up trading between the two states, the new single quota price would be some average of the quota market prices before integration (assuming one to one trading). To capture these ideas within our set-up, we solve the Federal problem (Eq. (S4)) except that now we impose that the marginal values (shadow prices) are equal in each period. Rearranging Eq. (S6) for both states, the shadow price constraint imposed on the system in each period is:

$$\frac{(p_i q_i x_i(t) - c_{i1} - 2c_{i2}E_i(t))}{q_i x_i(t)} = \frac{(p_j q_j x_j(t) - c_{j1} - 2c_{j2}E_j(t))}{q_j x_j(t)} \tag{S14}$$

Given our assumptions on homogeneous unit prices and catchability coefficients, we can write Eq. (S14) as:

$$\frac{c_{i1} + 2c_{i2}E_i(t)}{qx_i(t)} = \frac{c_{j1} + 2c_{j2}E_j(t)}{qx_j(t)} \tag{S15}$$

Intuitively, the value of harvesting fish in any given location is a function of the standing stock, the costs of harvesting, the ability to harvest the standing stock, and the price of fish. Under our assumptions, the marginal costs of fishing ($\frac{MC_i(E_i(t))}{MC_j(E_j(t))}$) are in the same ratio as the standing stock ($\frac{x_i(t)}{x_j(t)}$) for all t. When this ratio is satisfied, the (marginal) value of harvesting a unit of fish in both places are equal (i.e., there is a single quota or shadow price).

In terms of the speed of the market dynamics relative to the dynamics of the fish stocks, we are imposing an assumption of a fast equilibrium in the quota market such that marginal values from fishing are always equal across states. The federal manager chooses effort levels in each state fishery to maximize the aggregate value of the fishery such that Eq. (S15) is met.

Using Eq. (S15), we can solve for state-level effort in state i as a function of the current stock in both states and effort in state j:

$$E_i(t) = \varepsilon_i^M(E_j(t), x_i(t), x_j(t)) = \frac{c_{j1}x_i(t) - c_{i1}x_j(t) + 2c_{j2}E_j(t)x_i(t)}{x_j(t)} \quad \text{(S16)}$$

The federal manager's problem corresponding to this policy is (let $j = 2$):

$$J^M = \max_{E_2(t)} \int_0^\infty \left[\pi_1(x_1(t), \varepsilon_1^M(E_j(t), x_1(t), x_2(t))) + \pi_2(x_2(t), E_2(t))\right] e^{-\delta t} dt \quad \text{(S17)}$$

This problem is once again subject to stock dynamics (Eq. (S1)), initial conditions (x_{10}, x_{20}), and a non-negativity constraint on $E_i(t)$. Assuming an interior solution exists, the current-value Hamiltonian for this problem is:

$$H^M(x_1(t), x_2(t), \lambda_1^M(t), \lambda_2^M(t), E_2(t)) = \quad \text{(S18)}$$
$$\pi_1(x_1(t), \varepsilon_1^M(E_2(t), x_1(t), x_2(t)) + \pi_2(x_2(t), E_2(t)) \quad \text{(S19)}$$
$$+ \lambda_1^M(t)F_1(x_1(t), x_2(t), \varepsilon_1^M(E_2(t), x_1(t), x_2(t))) \quad \text{(S20)}$$
$$+ \lambda_2^M(t)F_2(x_1(t), x_2(t), E_2(t))) \quad \text{(S21)}$$

Along with the non-negativity conditions, initial conditions, and the fish stock equations, the first order necessary conditions are:

$$\frac{\partial \pi_1}{\partial \varepsilon_1^M}\frac{\partial \varepsilon_1^M}{\partial E_2(t)} + \frac{\partial \pi_2}{\partial E_2(t)} + \lambda_1^M(t)\frac{\partial F_1}{\partial \varepsilon_1^M}\frac{\partial \varepsilon_1^M}{\partial E_2(t)} + \lambda_2^M(t)\frac{\partial F_2}{\partial E_2(t)} = 0 \quad \text{(S22)}$$

$$\dot{\lambda}_1^M(t) = \lambda_1^M(t)\left(\delta - \frac{\partial F_1}{\partial \varepsilon_1^M}\frac{\partial \varepsilon_1^M}{\partial x_1(t)} - \frac{\partial F_1}{\partial x_1(t)}\right) - \lambda_2^M(t)\frac{\partial F_2}{\partial x_1(t)} - \frac{\partial \pi_1}{\partial \varepsilon_1^M}\frac{\partial \varepsilon_1^M}{\partial x_2(t)} \quad \text{(S23)}$$

and

$$\dot{\lambda}_2^M(t) = \lambda_2^M(t)\left(\delta - \frac{\partial F_1}{\partial x_2(t)}\right) - \lambda_1^M(t)\left(\frac{\partial F_1}{\partial x_2(t)} + \frac{\partial F_1}{\partial \varepsilon_1^M}\frac{\partial \varepsilon_1^M}{\partial x_2(t)}\right) - \frac{\partial \pi_1}{\partial \varepsilon_1^M}\frac{\partial \varepsilon_1^M}{\partial x_2(t)} - \frac{\partial \pi_2}{\partial x_2(t)} \quad \text{(S24)}$$

S1.4 State management

We assume that state management (or decentralized management) results in states selecting effort levels $E_i^G(t)$ that maximize the NPV of profits generated in their own state only, conditional on the choices made the other state. This is a noncooperative differential game (1; 4). We describe the state-level problem in the Materials and Methods section in the main text. Conditional on an assumed path for the opposing states effort, the optimal choice of effort for state i resembles Eq. (S8), however the effort choice will in general be different due to the different current shadow value $\lambda_i^G(t)$ and the associated different value of the stock. When dispersal (d) is zero, the connection between the two states is severed and state-level management will be identical to the first-best federal solution described above.

Unfortunately, the structure of our model does not correspond to one of the special classes of differential games with closed-form solutions for Nash equilibrium control choices and the associated state variable dynamics. We describe our numerical approach in the next section.

S2 Numerical solution approach

We solve each model variant using a direct optimization approach based on pseudo-spectral collocation (5). This involves approximating the state and control variables using a collection of basis functions. The method is referred to as direct because the approximated states and controls are used to form a constrained nonlinear program (NLP). In this problem, the objective (e.g., the integral in Eq. (S4)) is maximized directly over the collocation points, subject to constraints including initial conditions and the state equation. While the current shadow values are not incorporated into this constrained NLP, they may be computed from the solution (5). An example of a bioeconomic application of pseudo-spectral collocation with an extended discussion of the numerical details is provided by Kling et al. (6).

We implement and solve our model in `Matlab`, using the `tomlab` optimization environment (7). While the federal management models are straightforward applications of pseudo-spectral methods, the decentralized game is significantly more challenging. To the best of our knowledge, this study is the first to use pseudo-spectral methods to solve for Nash equilibria of a dynamic game in natural resource economics. Prior applications appear in the applied mathematics and engineering literatures (e.g., (8; 9)). Our approach to finding Nash equilibria involves a loop, with the inner loop solving for the optimal time paths of effort for each state given the assumed choice of the other (and subject to constraints). Taking these as candidate solutions, we then calculate the net present value of profits summing both states. If the change in profit across outer steps falls below a tolerance level ($1e-6$), the algorithm terminates and open-loop Nash solutions for the decentralized game $(E_1^G(t), E_2^G(t))$ are recorded. This method has the advantage of computing stock dynamics associated with the policies automatically. To test for possible multiple solutions, we used different initial guesses that span the solution-parameter space and ran the model to convergence. Our search of the space did not find multiple solutions.

S3 Measuring the value to switch regimes

To determine whether in aggregate there are preferences to switch management regimes, we compare the net present value of staying at the status quo steady-state levels forever to the net present value of the transition to the new steady-state and the value of staying at that steady-state level for each period. We are asking the question: given that you are currently at a steady-state level, what is the value from switching today to a new regime forever? Switching to a new regime implies solving a new optimal control problem from that point forward under the assumptions of the new regime.

Specifically, the net present value of the status quo management steady-state ((x_i^{ss}, E_i^{ss}) with $i = 1, 2$) is:

$$NPV_{statusquo} = \frac{\pi_1(x_1^{ss}, E_1^{ss}) + \pi_2(x_2^{ss}, E_2^{ss})}{\delta} \tag{S25}$$

The net present value of the switch includes the transition and the new steady-state levels ((x_i^s, E_i^s) with $i = 1, 2$). Specifically, in the case, the net present value is:

$$NPV_{newregime} = \int_0^T ((\pi_1(x_1^*(t), E_1^*(t) + \pi_2(x_2^*(t), E_2^*(t))\, e^{-\delta_i t} \mathrm{d}t + e^{-\delta T} \left(\frac{\pi_1(x_1^s, E_1^s) + \pi_2(x_2^s, E_2^s)}{\delta} \right) \tag{S26}$$

Here, the initial conditions for the transition to the new management regime are (x_i^{ss}, E_i^{ss}) with $i = 1, 2$. We measure the gains from moving from the status quo by measuring the percent difference between Eq. S26 and Eq. S25.

S4 Baseline Parameter Levels

Table S1: Baseline parameter values

Parameter	Symbol	Value(s)
Intrinsic growth rate	r_i	0.85
Carrying capacity	K_i	1
Revenue per unit harvested	p_i	10
Cost of effort parameter	c_{i1}	2
Adjustment cost parameter	c_{i2}	.5
Discount rate	δ	0.04

In the sensitivity analysis in the main paper, growth rates or costs range from equal across the patches to double the other patches, and dispersal rates go from zero to $0.5 * r_i$.

S5 Supplemental Figures to main text

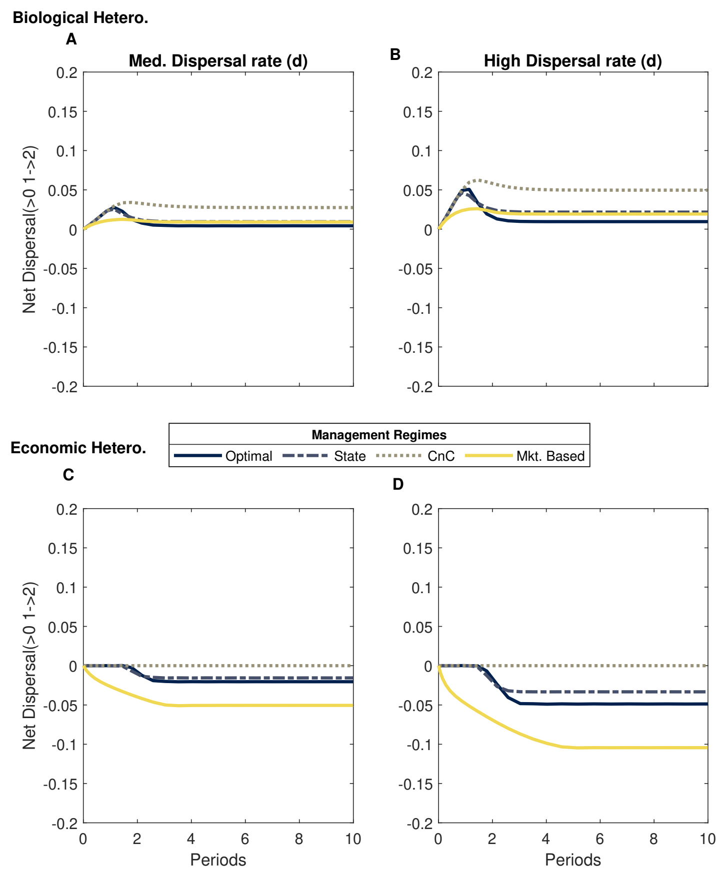

Figure S1: Net dispersal over time across the different management regimes under a medium (d is equal to approx. 70 percent of the maximum rate assumed in our analysis) and high dispersal (d is equal to approx. 97 percent of the maximum rate assumed in our analysis) and a high heterogeneity scenario (r_1 and c_{21} are both approx 62 percent greater than the other patches parameters, respectively). Net dispersal positive implies that biomass is moving from State 1 to State 2.

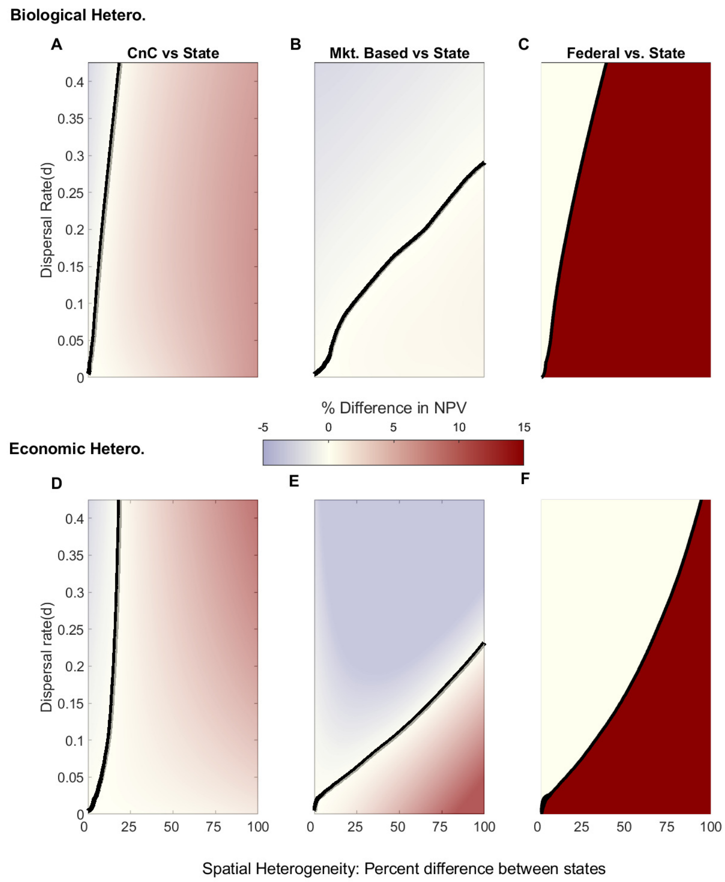

Figure S2: **State 1 Preferences** for federal vs. local control of an over-exploited resource under biological heterogeneity (Panels A, B, and C) and economic heterogeneity (Panels D, E, and F). For a given uniform federal management type (command and control or market-based), the heat map (panels A-B and D-E) measures the percent difference between the NPV of profits under state and federal management. In panels A-B and D-E, red zones indicate that state management performs better, while blue zones indicate that federal management performs better. Panels C and F, indicate absolute winner across all policies, where red signals state 1 management yields the highest payoff, white signals the federal market-based policy yields highest payoff, and blue signals the federal command and control policy yields the highest payoff for state 1. In all cases, the black contour lines represents zero, where there is no difference in economic performance between management regimes.

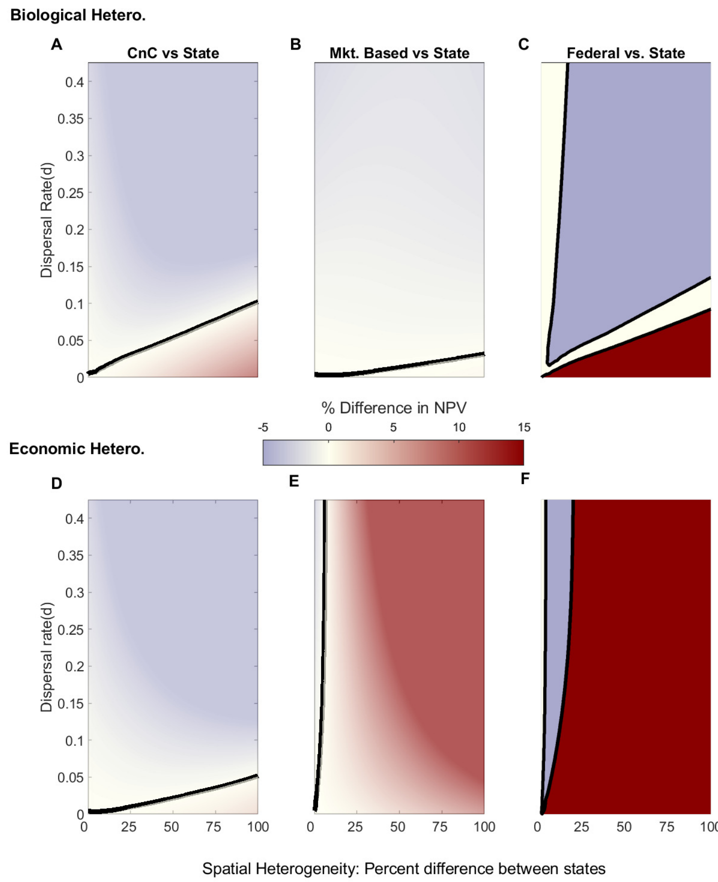

Figure S3: **State 2 Preferences** for federal vs. local control of an over-exploited resource under biological heterogeneity (Panels A, B, and C) and economic heterogeneity (Panels D, E, and F). For a given uniform federal management type (command and control or market-based), the heat map (panels A-B and D-E) measures the percent difference between the NPV of profits under state and federal management. In panels A-B and D-E, red zones indicate that state management performs better, while blue zones indicate that federal management performs better. Panels C and F, indicate absolute winner across all policies, where red signals state 2 management yields the highest payoff, white signals the federal market-based policy yields highest payoff, and blue signals the federal command and control policy yields the highest payoff for state 2. In all cases, the black contour lines represents zero, where there is no difference in economic performance between management regimes.

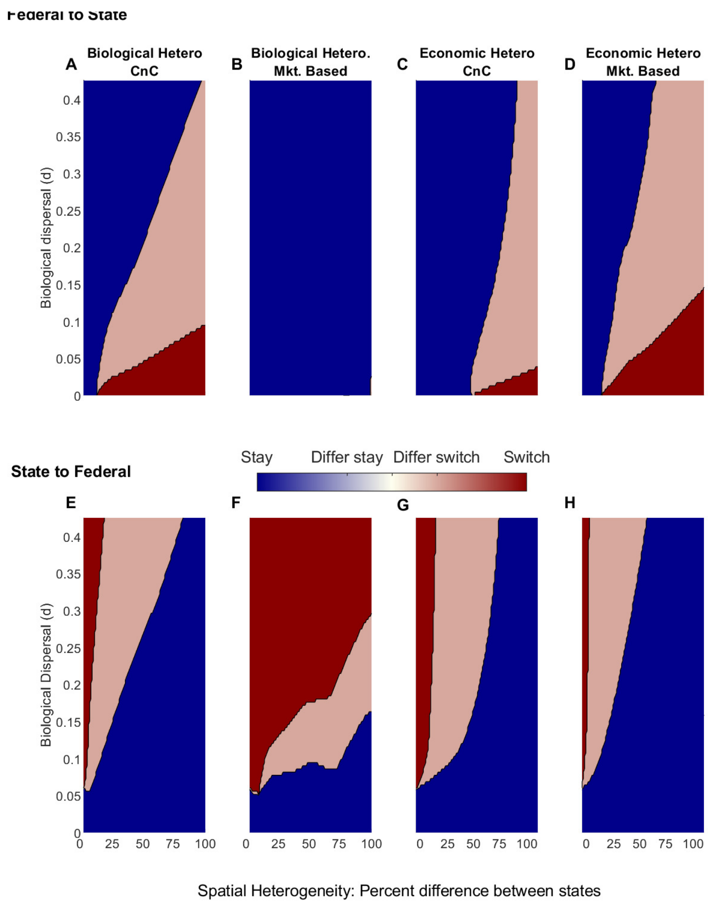

Figure S4: Preferences for switching management regimes. Rather than show the strength of the preferences in terms of the NPV differences, this map converts the preferences into a zero-one variable to clearly highlight the different regions. Dark red signals that both states prefer to switch regimes, dark blue that both prefer to remain in the states quo, and lighter colors represents differences in opinions on whether to remain or switch. If the color is light red (blue), then the state preferring to switch (remain) could compensate the state wanting to remain (switch). Federal (state) management is the status quo in the top (bottom) row. The first two columns represent biological heterogeneity and the last two columns represent economic heterogeneity. Columns 1 and 3 represent a federal uniform effort policy and columns 2 and 4 represent a federal market-based policy. In each panel, the initial conditions represent the status quo steady-state, which varies with the underlying heterogeneity (horizontal axis) and dispersal rate (vertical axis).

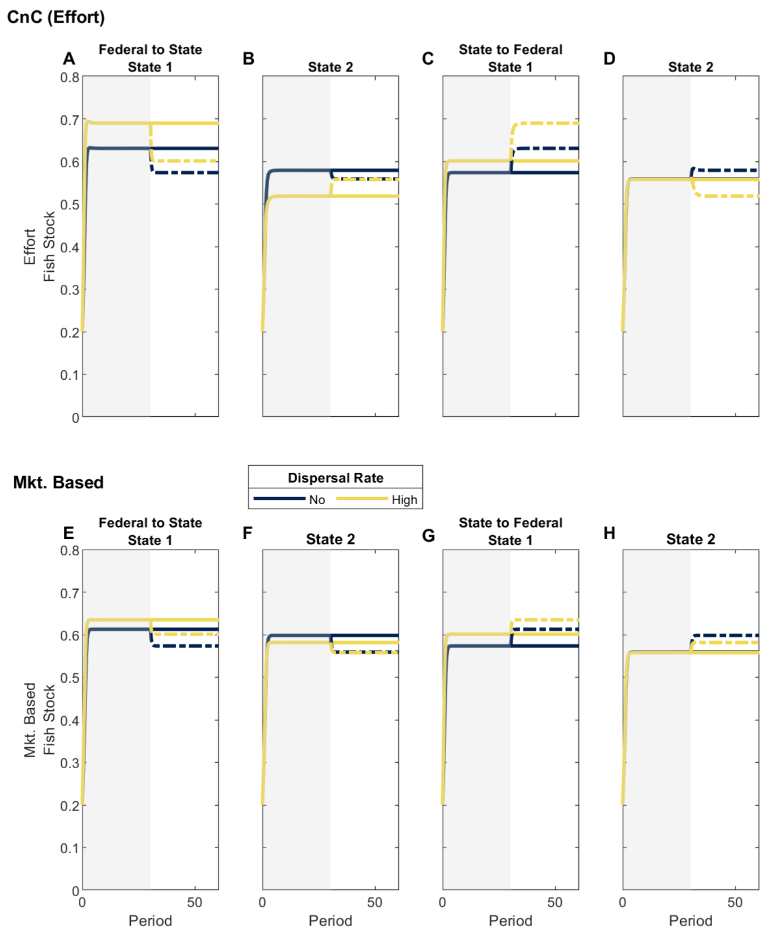

Figure S5: Example of the biomass adjustment paths from one management regime to another in the case of biological heterogeneity with no dispersal rate (blue lines) and a high dispersal rate(yellow lines)(97 percent of the maximum dispersal rate). For each parameter combination, there is a unique steady-state for the status quo, which is the starting initial condition for the transition to the new management regime. Grey shaded region represents the dynamics of the status quo from the over-exploited state and the white shaded regions are the adjustment paths to the new regime. The top row of panels (A-D) is the command and control federal to state switch and the bottom row of panels (E-H) is for the market-based federal policy to state switch. Panels A,B, E and F are when the status quo is federal management and panels C,D,G and H are when the status quo is state management.

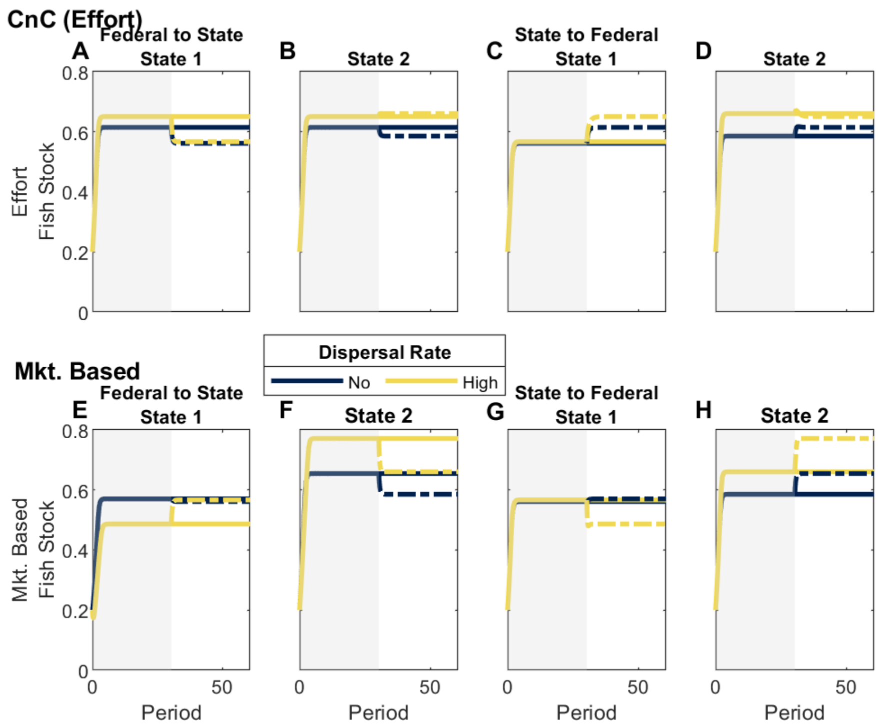

Figure S6: Example of the biomass adjustment paths from one management regime to another in the case of economic heterogeneity with no dispersal rate (blue lines) and a high dispersal rate(yellow lines) (97 percent of the maximum dispersal rate). For each parameter combination, there is a unique steady-state for the status quo, which is the starting initial condition for the transition to the new management regime. Grey shaded region represents the dynamics of the status quo from the over-exploited state and the white shaded regions are the adjustment paths to the new regime. The top row of panels (A-D) is the command and control federal to state switch and the bottom row of panels (E-H) is for the market-based federal policy to state switch. Panels A,B, E and F are when the status quo is federal management and panels C,D,G and H are when the status quo is state management.

S6 Sensitivity Analysis

S6.1 High Discount Rate

In this section, we present the cases with a high discount rate ($\delta = .10$).

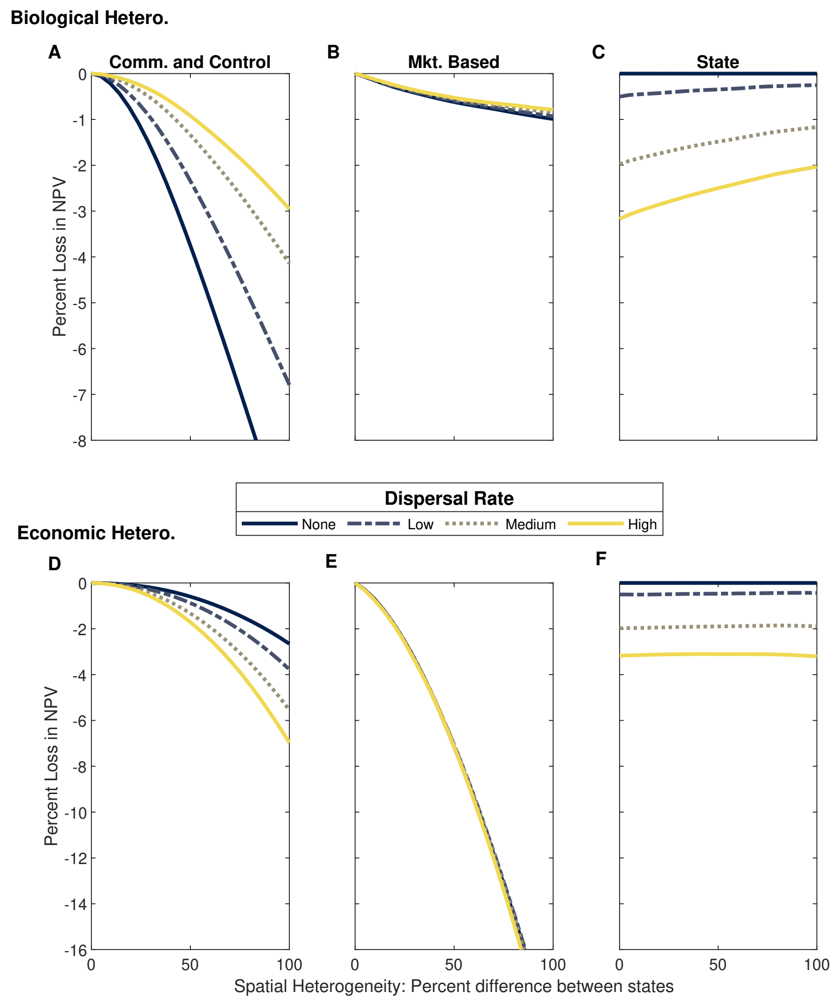

Figure S7: Percent loss in the NPV of profits under uniform federal and state management (vertical axis) relative to the first-best outcome. We measure percent loss varying the degree of inter-state heterogeneity along the horizontal axis. Within each panel, the four lines correspond to zero ($d = 0$), low ($d = .10$), medium ($d = .26$), and high ($d = .40$) dispersal rates. We consider two sources of heterogeneity (biological and economic). The top panels (A-C) show performance of the command and control (uniform effort), market-based regulation (uniform marginal rent), and state-level management with biological heterogeneity (percent difference in intrinsic growth rate (r_1) in state 1 relative to state 2). The bottom panels (D-F) consider the same three management types with economic heterogeneity (percent difference in cost of harvesting (c_{21}) in state 2 relative to state 1).

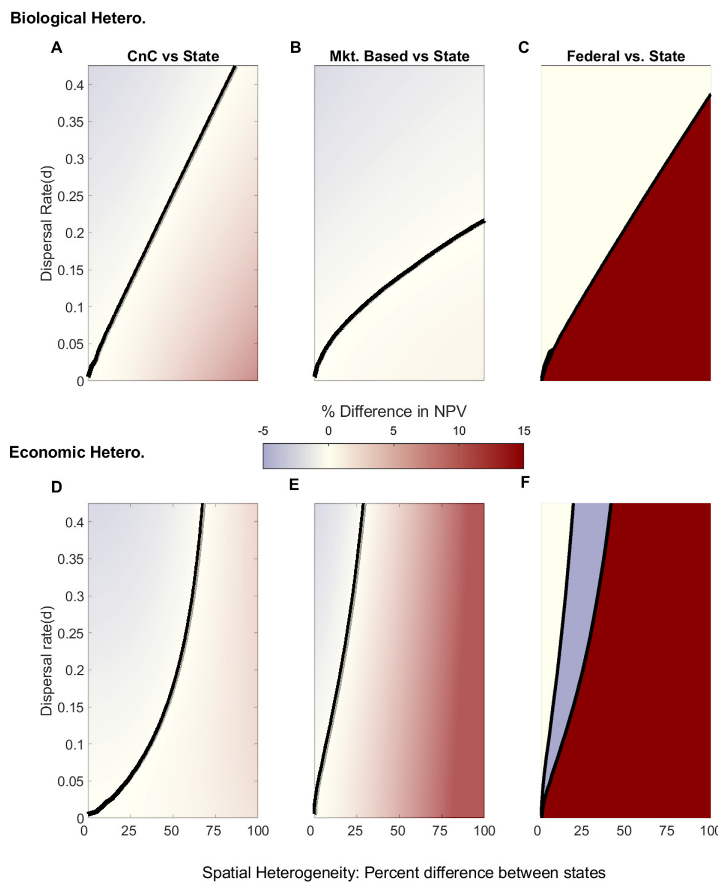

Figure S8: Federal vs. state management for an over-exploited resource under biological heterogeneity (Panels A, B, and C) and economic heterogeneity (Panels D, E, and F). For a given uniform federal management type (command and control or market-based), the heat map (panels A-B and D-E) measures the percent difference between the NPV of profits under state and federal management. In panels A-B and D-E, red zones indicate that state management performs better, while blue zones indicate that federal management performs better. Panels C and F, indicate absolute winner across all policies, where red signals state management yields the highest payoff, white signals the federal market-based policy yields highest payoff, and blue signals the federal command and control policy yields the highest payoff. In all cases, the black contour lines represents zero, where there is no difference in economic performance between management regimes.

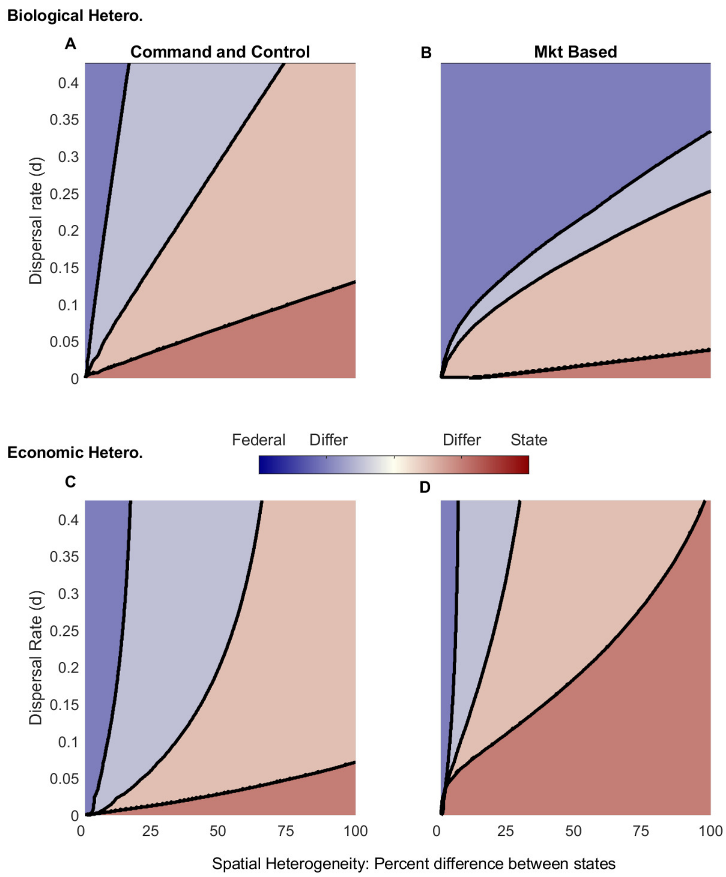

Figure S9: Fairness implications of federalism. All panels show the preferences of the states to different levels of management. Dark red indicates both states prefer state-level management, dark blue indicates both states prefer federal management. Light red (blue) indicates that one state prefers federal management and the other prefers state management but the total value of the resource is largest under state (federal) management. Preference is defined as differences in the state's net present value in the different management regimes. Panels A and B compare state management to federal management (command and control or market-based) with biological heterogeneity between states. Panels C and D compare state management to federal management (command and control or market-based) with economic heterogeneity between states.

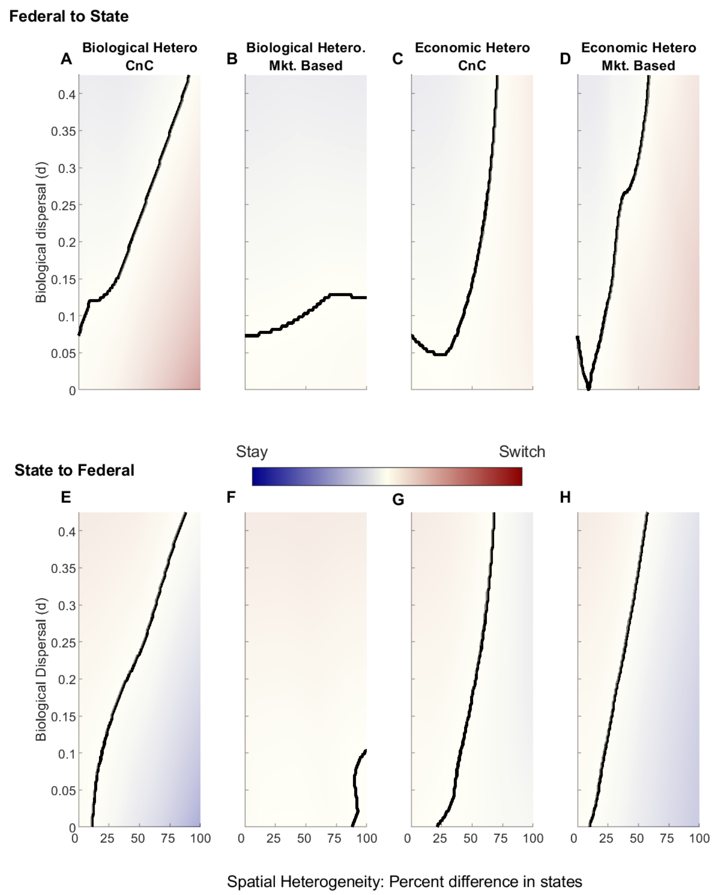

Figure S10: Preferences for switching management regimes. The heat map in each panel measures the percent difference between the NPV of profits under status quo management and a change in management regime. Federal (state) management is the status quo in the top (bottom) row. The first two columns represent biological heterogeneity and the last two columns represent economic heterogeneity. Columns 1 and 3 represent a federal uniform effort policy and columns 2 and 4 represent a federal market-based policy. In each panel, the initial conditions represent the status quo, which varies with the underlying heterogeneity (horizontal axis) and dispersal rate (vertical axis).

S6.2 Low Discount Rate

This section provides results assuming a low discount rate ($\delta \simeq 0$).

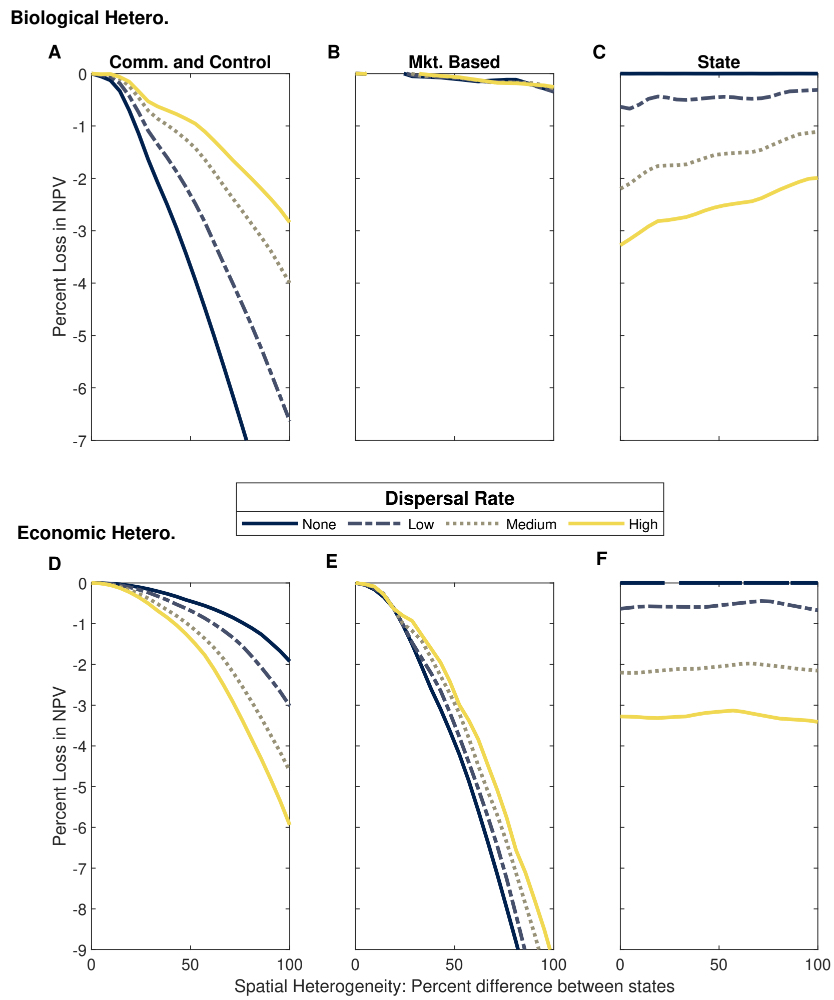

Figure S11: Percent loss in the NPV of profits under uniform federal and state management (vertical axis) relative to the first-best outcome. We measure percent loss varying the degree of inter-state heterogeneity along the horizontal axis. Within each panel, the four lines correspond to zero ($d = 0$), low ($d = .10$), medium ($d = .26$), and high ($d = .40$) dispersal rates. We consider two sources of heterogeneity (biological and economic). The top panels (A-C) show performance of the command and control (uniform effort), market-based regulation (uniform marginal rent), and state-level management with biological heterogeneity (percent difference in intrinsic growth rate (r_1) in state 1 relative to state 2). The bottom panels (D-F) consider the same three management types with economic heterogeneity (percent difference in cost of harvesting (c_{21}) in state 2 relative to state 1).

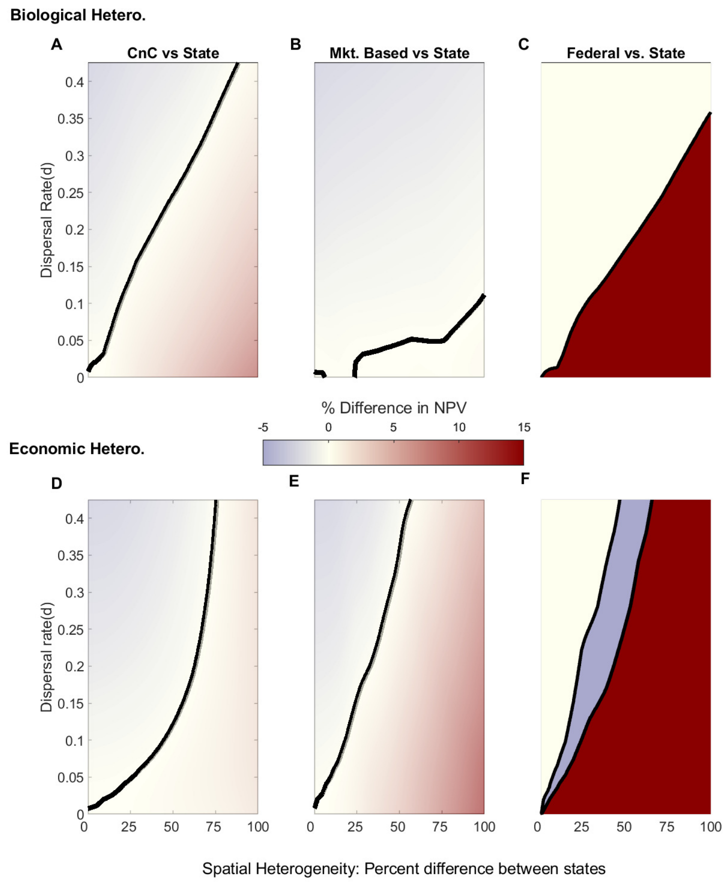

Figure S12: Federal vs. state management for an over-exploited resource under biological heterogeneity (Panels A, B, and C) and economic heterogeneity (Panels D, E, and F). For a given uniform federal management type (command and control or market-based), the heat map (panels A-B and D-E) measures the percent difference between the NPV of profits under state and federal management. In panels A-B and D-E, red zones indicate that state management performs better, while blue zones indicate that federal management performs better. Panels C and F, indicate absolute winner across all policies, where red signals state management yields the highest payoff, white signals the federal market-based policy yields highest payoff, and blue signals the federal command and control policy yields the highest payoff. In all cases, the black contour lines represents zero, where there is no difference in economic performance between management regimes.

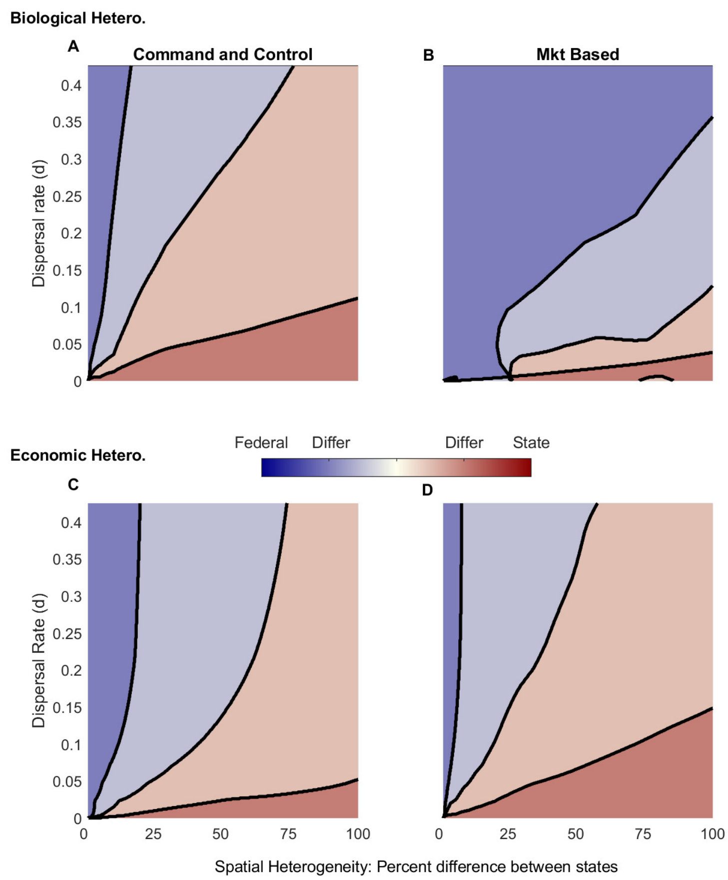

Figure S13: Fairness implications of federalism. All panels show the preferences of the states to different levels of management. Dark red indicates both states prefer state-level management, dark blue indicates both states prefer federal management. Light red (blue) indicates that one state prefers federal management and the other prefers state management but the total value of the resource is largest under state (federal) management. Preference is defined as differences in the state's net present value in the different management regimes. Panels A and B compare state management to federal management (command and control or market-based) with biological heterogeneity between states. Panels C and D compare state management to federal management (command and control or market-based) with economic heterogeneity between states.

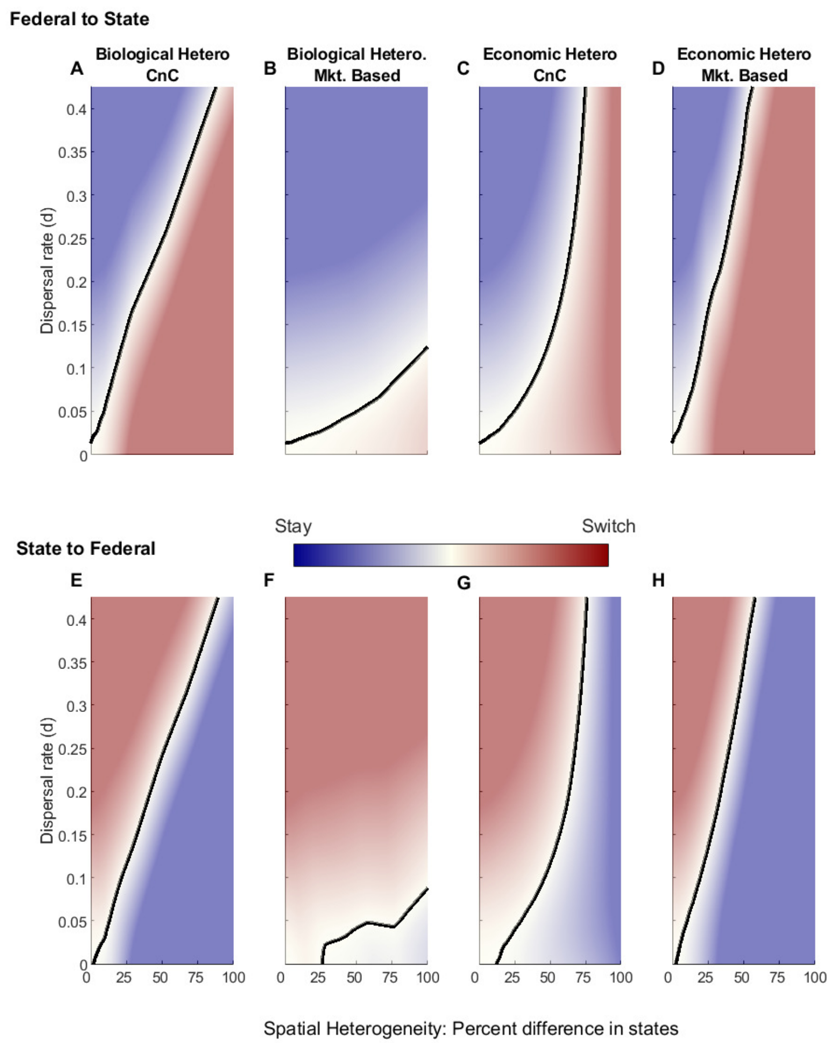

Figure S14: Preferences for switching management regimes. The heat map in each panel measures the percent difference between the NPV of profits under status quo management and a change in management regime. Federal (state) management is the status quo in the top (bottom) row. The first two columns represent biological heterogeneity and the last two columns represent economic heterogeneity. Columns 1 and 3 represent a federal uniform effort policy and columns 2 and 4 represent a federal market-based policy. In each panel, the initial conditions represent the status quo, which varies with the underlying heterogeneity (horizontal axis) and dispersal rate (vertical axis). Relative to the other cases, the magnitude of these differences are significantly greater but the overall pattern is very similar.

S6.3 Unexploited Initial Conditions of Fish Stocks

Results in this section assume a relatively unexploited fish stock level (80% of K), where the dynamic paths of fishing effort and fish stock capture fishing down the stock to their new steady-state levels.

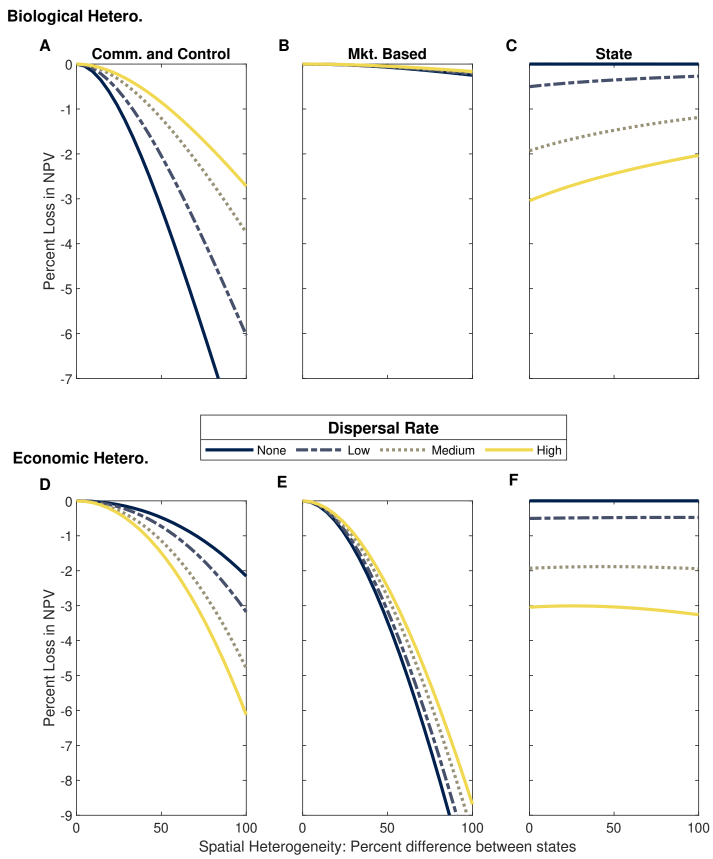

Figure S15: Percent loss in the NPV of profits under uniform federal and state management (vertical axis) relative to the first-best outcome. We measure percent loss varying the degree of inter-state heterogeneity along the horizontal axis. Within each panel, the four lines correspond to zero ($d = 0$), low ($d = .10$), medium ($d = .26$), and high ($d = .40$) dispersal rates. We consider two sources of heterogeneity (biological and economic). The top panels (A-C) show performance of the command and control (uniform effort), market-based regulation (uniform marginal rent), and state-level management with biological heterogeneity (percent difference in intrinsic growth rate (r_1) in state 1 relative to state 2). The bottom panels (D-F) consider the same three management types with economic heterogeneity (percent difference in cost of harvesting (c_{21}) in state 2 relative to state 1).

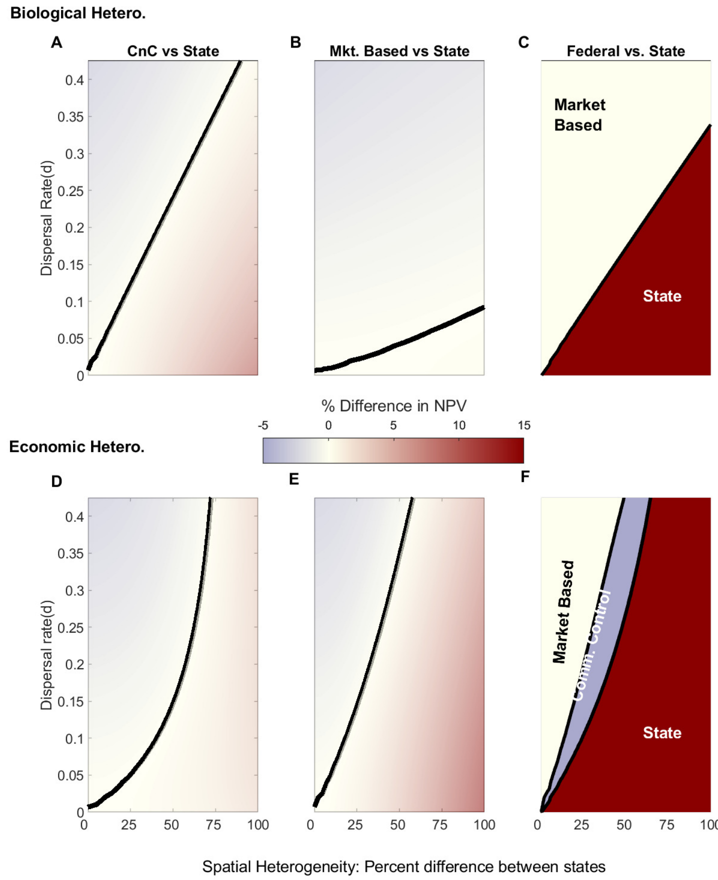

Figure S16: Federal vs. state management for an over-exploited resource under biological heterogeneity (Panels A, B, and C) and economic heterogeneity (Panels D, E, and F). For a given uniform federal management type (command and control or market-based), the heat map (panels A-B and D-E) measures the percent difference between the NPV of profits under state and federal management. In panels A-B and D-E, red zones indicate that state management performs better, while blue zones indicate that federal management performs better. Panels C and F, indicate absolute winner across all policies, where red signals state management yields the highest payoff, white signals the federal market-based policy yields highest payoff, and blue signals the federal command and control policy yields the highest payoff. In all cases, the black contour lines represents zero, where there is no difference in economic performance between management regimes.

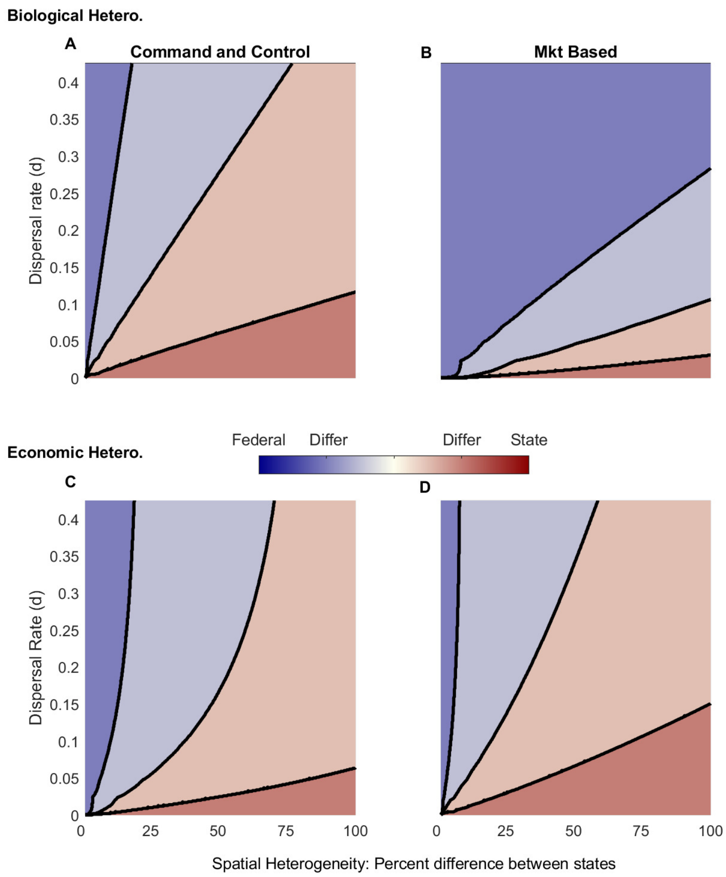

Figure S17: Fairness implications of federalism. All panels show the preferences of the states to different levels of management. Dark red indicates both states prefer state-level management, dark blue indicates both states prefer federal management. Light red (blue) indicates that one state prefers federal management and the other prefers state management but the total value of the resource is largest under state (federal) management. Preference is defined as differences in the state's net present value in the different management regimes. Panels A and B compare state management to federal management (command and control or market-based) with biological heterogeneity between states. Panels C and D compare state management to federal management (command and control or market-based) with economic heterogeneity between states.

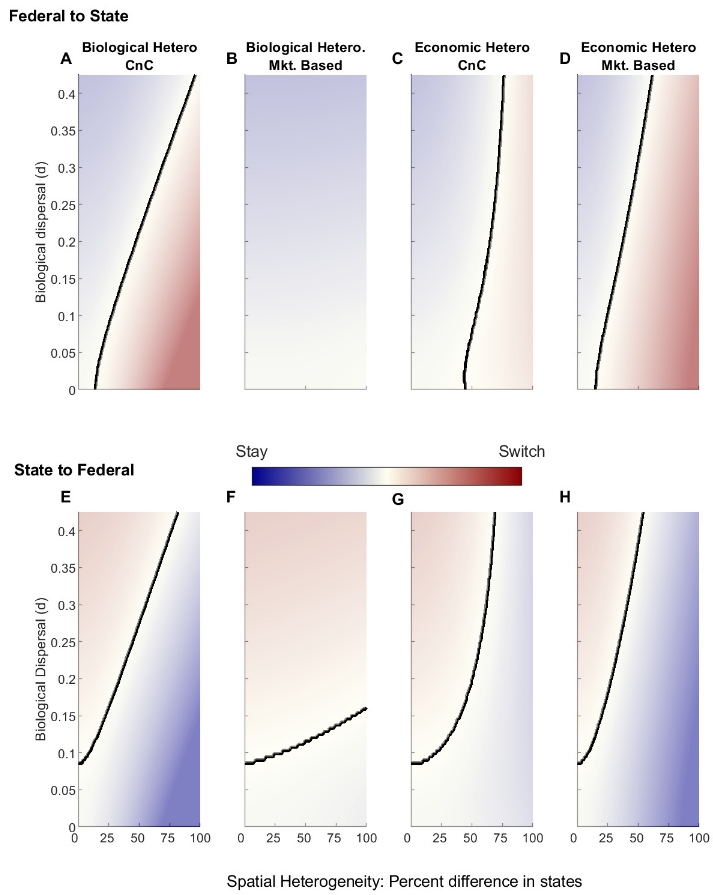

Figure S18: Preferences for switching management regimes. The heat map in each panel measures the percent difference between the NPV of profits under status quo management and a change in management regime. Federal (state) management is the status quo in the top (bottom) row. The first two columns represent biological heterogeneity and the last two columns represent economic heterogeneity. Columns 1 and 3 represent a federal uniform effort policy and columns 2 and 4 represent a federal market-based policy. In each panel, the initial conditions represent the status quo, which varies with the underlying heterogeneity (horizontal axis) and dispersal rate (vertical axis).

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