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The social dynamics of natural resources management: Dynamical systems modeling approaches to understanding equity, power, and system responses to change

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The social dynamics of natural resources management: Dynamical systems modeling approaches to understanding equity, power, and system responses to change

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Abstract

The social-ecological systems paradigm emerged as an alternative to traditional approaches to natural resources management, bringing together a complex systems approach rooted in multi-equilibrium ecology that emphasizes managing feedbacks and transformations, a recognition of the intertwined nature of social and environmental dynamics, and a focus on institutions as a means of addressing collective action problems. However, despite the promise of this paradigm in integrating the social and natural sciences of natural resources management and governance, insights and methods from the complexity sciences have yet to be fully harnessed in understanding the social-ecological dynamics of natural resources, while social-ecological systems models tend to fall short in capturing the aspects of human systems that are distinct from ecological systems; namely, self-organization, heterogeneity, and subjectivity. This dissertation develops dynamical systems modeling approaches that address this gap in exploring how these dynamics shape system responses to change and differentiated outcomes. The first chapter develops a dynamical systems model of communities that are economically dependent on natural resource exploitation (e.g. mining, logging, and industrial agriculture communities) that links resource dynamics, migration, and community wellbeing. The results reveal an inevitable misalignment between policies that support a higher quality of life for communities and those that ensure resilience of the industry, and the temporal dynamics of this misalignment. To explore how the structure of resource governance shapes its function, Chapter 2 uses a generalized version of dynamical systems modeling to develop a modeling approach for linking system aspects, such as diversity, heterogeneity, and connectivity, correspond to stability. The results reveal that greater complexity – greater diversity of stakeholders and decisionmakers and greater interdependence among actors – corresponds to lower stability, while strategies such as venue shopping and a greater number and diversity of non-government organizations are stabilizing. Finally, the final chapter draws on the general principles and methods from the previous chapters in the context of the San Joaquin Valley (SJV), an industrial agriculture-dominated region that is rife with inequality and with rapidly degrading groundwater, to explore actors' strategies, narratives, and power in shaping how water governance and agriculture in the SJV change. Narrative analysis of interviews and focus groups with growers, various advocacy groups, and residents of rural communities alongside modeling of actors' interactions with each other and with water is used to explore how these narratives influence actors' strategies for enacting change, and the implications of their envisioned changes for how different groups can influence and are influenced by each other. The results reveal how the structure of agriculture and water governance create a conflict for small growers and rural communities between seeking more just distribution of the benefits from water consumption and increasing their water access within the status quo, which tends to channel most of the benefits of water management to larger growers. Overall, this dissertation develops complex systems approaches to understanding how linked natural and social dynamics shape the resilience and equity of natural resources exploitation and governance systems, yielding methodologies that can be applied to diverse cases, general principles for natural resources governance and resource-based communities, and concrete insights for guiding management and transformation of these systems.

Introduction and Background

The multiple linked environmental crises facing society and the failure of traditional engineering and economics-driven management has led rise to a new paradigm for natural resources management. This new paradigm brings together the study of the environment and natural resources, complexity science, and governance and institutions in recognizing that 1) social and natural processes are intertwined, and thus should be studied together, 2) these processes are complex, meaning that there are non-linearities and emergent behavior that traditional approaches cannot foresee, and 3) that alternative knowledge systems, including local knowledge/lived experience provides insights into managing these complex processes (Berkes, Folke, and Colding, 1998; Folke, Hahn, et al., 2005; Folke, 2006; Folke, Biggs, et al., 2016; Liu et al., 2007). This final point is a consequence of the fact that acknowledging complexity demands more than just conceptualizing social and ecological processes differently. Rather, it demands a different outlook on the production and role of "expert" knowledge, which in its often narrow and myopic focus, has often fallen short in guiding land use and natural resources management systems that are resilient in the long term, in contrast to the knowledge and practices of cultures that have evolved alongside their environment for thousands of years to manage, for example, complex food webs, soil health and biodiversity, and fire-dependent landscapes (Berkes, Folke, and Colding, 1998; Berkes, Colding, and Folke, 2000; Berkes, 2012).

This outlook does not preclude the value of expert knowledge and methods such as modeling. Instead, it implies a different approach to modeling. Complex systems modeling is focused on understanding broad dynamics and qualitative behavior, rather than prediction. The models, therefore, consist of relatively fewer variables and represent fewer processes. However, these models have led to insights into how the structural attributes of systems determine their response to change, such as that complexity tends to lead to instability, that certain predator-prey ratios lead to robust ecosystems, or that disassortative network structures, such as those of pollinators and the plants they pollinate, can better withstand perturbations (May, 1972; May, Levin, and Sugihara, 2008; Gross et al., 2009).

While complexity approaches have led to important insights, especially in ecological systems, applying them to human systems introduces unique challenges and considerations. One is that while stability and robustness are generally desirable in ecosystems, they are much more fraught in the context of human systems, in which many undesirable qualities, such as inequality and tyranny, are also unfortunately persistent (Cote and Nightingale, 2012; Nightingale, 2015; Ingalls and Stedman, 2016). Thus, a complex systems approach to human systems needs to recognize that different system pathways and states imply different winners and losers, and thus are contested. Models therefore need to disaggregate and differentiate among these groups that stand to win or lose in different system configurations. Another challenge is that characterizing the system is itself less straightforward and contested when these systems are socially constructed rather than consisting of physical, measurable interactions. Modeling human systems therefore needs to account for this inherent uncertainty and ambiguity through methods that allow for exploring different assumptions regarding parameterization and even structure. This is fortunately something that complex systems methods are suited to due to the relative simplicity of models and analysis methods that allow for quickly gaining insight into the effects of different processes and variables in shaping system behavior. Finally, in addition to the characterization of social systems being contested, the way that they are perceived and understood is not independent of how they function. The function of governance in particular is heavily dependent on legitimacy, trust, and norms that shape how people interact with governance and self-regulate. Complex systems approaches can therefore benefit from engaging with the social sciences of how people create different system understandings and act on them.

The methods and models developed in this dissertation aim to address these considerations in the context of resource exploitation, particularly in rural communities dependent on intensive resource extraction, and the governance systems that manage them. Chapter 1 develops a model of resource-based communities that includes the dynamics and wellbeing of the workers and community that make extraction or production possible and bear the brunt of its environmental and social costs, in contrast to the many bio-economic models that focus only on the dynamics of extraction and production. Recognizing that the resilience of this system of production is not necessarily desirable, this model then explores the relationship between resilience and community wellbeing as mediated by different policies regulating extraction. Chapter 2 zooms out to explore the governance structures that determine how resources are managed, and how their characteristics determine how they respond to change through developing a modeling approach that allows for exploring many different possible system structures. Chapter 3 then draws on this modeling approach in exploring how narratives and strategies of different actors in the San Joaquin Valley interact, and the implications of these narratives for the vulnerability and power of these different actors. This dissertation thus represents a starting point for better integrating the unique aspects of social systems in using complex systems modeling to understand how to create more sustainable and equitable social-ecological systems.

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Chapter 1

Resilience–Equity Dynamics in resource-based communities[1]

1.1 Abstract

Despite the growing focus on understanding how to build resilience, the interaction between resilience and equity, particularly in the context of power asymmetries like those in communities reliant on resource-based industries, or resource-based communities, is not well understood. Here we present a stylized dynamical systems model of asymmetric resource access and control in resource-based communities that links industrial resource degradation, community well-being, and migration in response to economic and resource conditions. The model reveals a mechanism of collapse due to these dynamics in which over-extraction and resource degradation trigger irreversible population decline. Regulating resource extraction can increase resilience (in the sense of persistence) while also shifting the sustainable equilibrium and the implications for equity. Resilience does not guarantee equity at equilibrium, and this misalignment is more pronounced in the transient interactions between short term equity

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and long term resilience. The misalignment between resilience and equity demonstrates how equity considerations change the policy design process in important ways.

1.2 Introduction

The scale and intensity of human-induced environmental change exacerbate the need to manage natural resources sustainably and equitably, especially for those most vulnerable to its effects. This is particularly true in rural communities that rely on a single externally-controlled industry based on capital-intensive resource extraction, or resource-based communities (RBCs) (Sander-Regier et al., 2009; Thomas and Twyman, 2005). RBCs represent a unique intersection between intense environmental degradation and disparities in resource access and control. The social and economic characteristics of resource-based communities and their vulnerability to economic and resource shocks have been documented through numerous case studies in forestry, mining, and coastal communities in Canada and the U.S (Tsenkova and Youssef, 2014). While these communities are diverse, they share characteristics like high transience, under-investment in local infrastructure and services, and lack of alternative economic opportunities (Parkins and Angell, 2011; Tsenkova and Youssef, 2014). For example, communities in Appalachia with origins as coal camps struggle with the legacy of headwaters destruction and heavy metals pollution alongside lack of investment in public infrastructure and the development of social capital (Swick, 2014). California's prolific agricultural industry exists alongside farmworker communities that suffer from poverty, water polluted by fertilizer and pesticides, and dry wells (Greene, 2018; Pannu, 2012).

1.2.1 Resource-Based Communities as Social-Ecological Systems

Resource-based communities have long been a subject of study in rural sociology, community development, and political economy. These studies have traditionally focused on understanding the trajectory of resource-based communities, the impacts of the 'booms' and 'busts' that are common features of these trajectories on community social capital and wellbeing (Deacon, 2015; Dolan et al., 2005), the persistence of disproportionate rates of poverty, and the land ownership and tenure patterns that tend to correspond to different development trajectories. The literature documents the particular vulnerability of RBCs to economic downturns due to fluctuations in commodity prices and the degradation of the resource base on which extraction relies (Freudenburg, 1992), exacerbated by the lack of funding for infrastructure, education, and social services caused by tax policies that tend to favor extra-local corporate landowners, causing much of the benefits of production to flow out of the community (Gaventa, 1995; Swick, 2014). Studies on the political economy of RBCs have examined the concentration of land and resource rights in the hands of a few, and the tendency for corruption and corporate capture of the state (Gaventa, 1995; Swick, 2014).

RBCs lend themselves to being studied from a social-ecological perspective, given the intimate coupling of human well-being and local natural processes and distinct spatial boundaries. Yet, the social-ecological systems (SES) literature tend to focus on smallholder dominated systems, and on understanding the conditions under which the cooperation and collective action emerges endogenously among relatively homogeneous resource users (Muneepeerakul and J. M. Anderies, 2017; Yu et al., 2015; J. M. Anderies, 2015; Ostrom, 1999). This approach de-emphasizes intra-group dynamics, conflict, and the equity concerns arising from power imbalances among users (Fabinyi, Evans, and Foale, 2014; Epstein et al., 2014; Agrawal, 2003). However, the SES literature still provides important insights for understanding social-natural interactions and how they relate to the resilience of communities and the natural resource wealth on which they rely.

Given the distinct challenges RBCs face and their suitability to being studied as social-ecological systems, they serve as a natural confluence of two disparate strands of resilience research: community resilience and “ecological” resilience (Berkes and Ross, 2013). Community resilience, which is most commonly referred to within the community development and risk and disaster literatures, evolved from the health and developmental psychology tradition (Berkes and Ross, 2013). Community resilience conceptualizes resilience as an episodic process of growth and adaptation, rather than as an outcome. Studies have proposed that active local organizations and organizational networks, the presence of community leadership, and strong social safety nets, among other factors, contribute to the process of building community resilience (Norris et al., 2008; Kulig, Edge, and Joyce, 2008). On the other hand, ecological resilience is based on observations of the dynamics of ecosystems with their uncertainties, abrupt and nonlinear shifts, and multiple stable states, and is defined as the capacity of a system to withstand disturbances while remaining within critical thresholds in which it retains its basic function (Holling, 1973; Folke, 2006). Ecological resilience is a characteristic of systems rather than of any single component. Unlike with community resilience, ecological resilience does not necessarily imply equity – for example, poverty traps are a state of system functioning that is both resilient and undesirable (Lade et al., 2017; Folke, 2006). Emerging concepts of resilience such as *social*-ecological resilience emphasize the ability of a system to transform and adapt rather than just persist in a potentially undesirable form. However, the concept of persistence as defined by ecological resilience is still a useful and influential one that tends to be mistakenly conflated with the same positive features as community and social-ecological resilience (Fabinyi, Evans, and Foale, 2014; Folke, 2006; Folke, 2015). Thus, there remains a need to distinguish the equity implications of ecological resilience from the more transformative changes that might be implied by other understandings of resilience (Cote and Nightingale, 2012; Ingalls and Stedman, 2016).

There are many case studies suggesting the potential for tradeoffs between equity and other resource management objectives such as economic return, and conservation goals (Halpern et al., 2013; Daw et al., 2015). Similarly, studies on the asymmetric commons dilemma suggest tradeoffs between increased system robustness and inequality (Yu et al., 2015), and that technology can lead to self-reinforcing inequities (Mirza et al., 2019). The emerging literature on the social implications of resilience critically analyzes for whom and to what the system is resilient, revealing the differential benefits of resilient systems and their tradeoffs across spatial and temporal scales. For example, a historical case study of the Faroe islands documents how ecological catastrophe was averted at the cost of maintaining and reinforcing exclusionary resource access policies and high levels of social inequality (Brewington, 2017), and a study of the resilience of water management in South Africa over time found tradeoffs between short term resilience that benefited the powerful and long-term resilience with broader benefits (Bohensky, 2008). While there are many individual case studies documenting conflicts between resilience and equity as well as analyses of the shortcomings of the concept of resilience for understanding issues of equity and power (Fabinyi, Evans, and Foale, 2014; Cote and Nightingale, 2012), there is still much more focus on deriving the principles for building resilience rather than for identifying the circumstances in which it is desirable with regards to equity (Folke, 2015; Folke, 2006). This study contributes to bridging the gap between individual case studies and a broader theory on resilience-equity interactions by investigating the interaction between ecological resilience and equity in a more general setting while still incorporating potentially important and oft-overlooked factors like social differences and power asymmetries that are specific to RBCs. Stylized theoretical models have often been used for this purpose, such as in studying when cooperation and self-governance emerges in social-ecological systems (Muneepeerakul and J. M. Anderies, 2017; Yu et al., 2015; Auer et al., 2015; Berardo and Scholz, 2010; Gómez-Gardeñes et al., 2012). Dynamical systems modeling in particular offers an intuitive understanding of ecological resilience (Muneepeerakul and J. M. Anderies, 2020; Gunderson, 2000; Folke, 2006), and the level of disaggregation allows for examining equity within a low-dimensional system.

The study proceeds as follows. First we introduce the dynamical systems model, which links industrial natural resource consumption and the dynamics of the natural resource system, wages, and migration. The analysis of the model consists of two parts. In “System Dynamics and Equilibria,” we examine the qualitatively different equilibria that result from the model dynamics, and how regulating extraction can intervene in these dynamics. The results reveal how the failure of resource-based communities to sustain livelihoods depends as much on the social dynamics of migration and how communities experience resource degradation as on the natural dynamics of resource degradation itself, and how regulating resource extraction can mitigate these effects to increase system resilience. In the second part of the analysis, "Governance Challenges and Tradeoffs," we consider the interaction between resilience and equity at different timescales. This approach balances conceptual simplicity with the incorporation of sufficient social complexity to explore potential governance challenges that arise in resource-based communities.

1.3 Methods

In order to study the fundamental asymmetry at the heart of resource-based communities, we propose a model that includes both industrial users, who have access to infrastructure and other inputs needed to profit from resource extraction, and domestic users, who use or otherwise benefit from the resource, but are unable to create a livelihood from the resource except through wage labor for industrial users (Figure 1.1). This level of aggregation and expanding the focus of the model to include actors that do not have a significant direct impact on the resource but impact the system nonetheless allows us to explore the inequality between these groups with different levels of control and access to the resource, better capturing issues of power than either modeling inequality among individuals or aggregating all resource users. The model consists of three interacting state variables: the resource state R, community population U, and the wage W. These variables are additionally mediated by the industrial users' extraction, which is modeled as an optimization constrained by the resource state and community population, which serves as the labor force for the industry. Their extraction decisions, in turn, affect the resource state and the availability of employment and wage for the community. The resource state, wage, and availability of employment determine the overall quality of life for community residents, which affects how the population migrates in or out of the community. The model thus captures the intertwined dynamics of the resource, extraction, and migration in resource-based communities. The model structure embeds power disparities in two ways: 1) Despite relying on the resource to fulfill their basic needs, the community lacks access to the infrastructure and capital needed to impact it to the extent the industrial users do, and 2) The community benefits only through the wages they receive, and do not benefit directly from profits generated by resource extraction despite bearing the cost of resource degradation. The details of the model equations are presented below.

1.3.1 Industrial User Production Function

Since industries typically have far greater technological and financial capital than domestic resource users, changes in the resource state are modeled as determined entirely by industrial users. Industrial users maximize their profit P with respect to labor L and resource extraction E (Equation 1.1), constrained by the availability of labor and the resource. The first term measures revenue using the general form of a constant elasticity of substitution (CES) production function typically used to represent the relationship between the inputs, typically physical capital and labor, and the amount of output that can be produced by those inputs. In this case, the variable inputs are the resource and labor, and the third input, meant to represent fixed inputs such as land, is held constant. The second term represents the extraction cost, which is proportional to the difference between the resource maximum capacity and the current state of the resource (analogous to the drawdown for an aquifer, for example), and the third term represents the labor cost. Marginal extraction costs increase as the resource is depleted or degraded, as is the case, for example, with groundwater extraction as the water table drops and more energy and/or deeper wells are required.

$$\max_{E,L} P = a\left(b_1 E^q + b_2 L^q + 1\right)^{1/q} - c\left(1 - R\right)E - WL - d - T(E) \tag{1.1}$$

subject to the constraints $0 \leq E \leq R$ and $0 \leq L \leq U$. The parameter a represents the revenue threshold at which the marginal benefit of resource and labor approaches zero, q is the substitution parameter, $b_1$and b_2 represent the share parameters associated with resource and labor, respectively, c represents the extraction cost parameter, and d represents a fixed cost. $T(E)$ represents the cost imposed by the policy, and is described in greater in detail in the Policies section (Equations 1.6).

The optimization is modeled as deterministic, and industrial users have perfect information about the current resource and labor available. The optimization is therefore constrained by the available resource and labor. However, industrial users are modeled as myopic, optimizing only over the short term with no knowledge of resource or labor dynamics, consistent with the behavior of users in general common-pool resource dilemmas.(Kollock, 1998) The impact of industry on the resource state in the model is referred to as resource use or extraction, though changes in resource state can represent a reduction in either quantity or quality of the resource.

1.3.2 Wage Dynamics

The wage changes based on the marginal increase in profit of additional labor, $\frac{\partial P}{\partial L}$, as shown in Equation 1.2. This relationship is meant to represent how wages increase when labor is a constraining factor for production, and decrease when there is excess labor.

$$\frac{dW}{dt} = \begin{cases} g\frac{\partial P}{\partial L} & \frac{\partial P}{\partial L} > 0 \\ -h(U-L) & \frac{\partial P}{\partial L} = 0 \end{cases} \tag{1.2}$$

where g and h are parameters modulating the rates at which the wage increases or decreases, respectively.

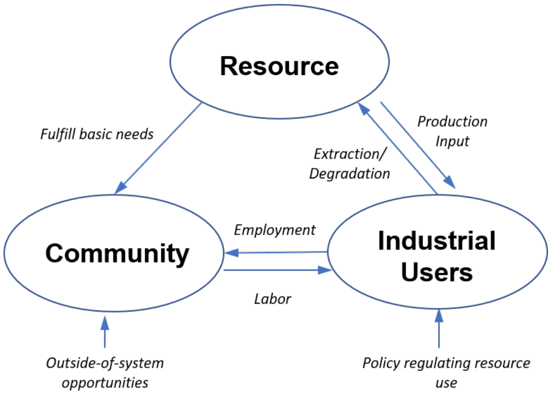


Figure 1.1: Schematic of the proposed model. The resource serves as a production input for the industrial users, who profit from extracting the resource, and fulfills the basic needs of the community, who does not extract the resource. The industrial users optimize both the amount they extract and the amount of labor used, which is provided by the community. The amount of labor they use relative to the community population determines how the wages increase or decrease. The community wellbeing is based on their wages from employment by industrial users and access to the resource to fulfill their needs. Finally, the community migrates in and out of the system based on how this wellbeing compares to a constant outside-of-system wellbeing.

1.3.3 Resource Dynamics

The dynamics of the resource follows a simple mass balance relationship between a constant natural regeneration, r, a natural loss rate, and the extraction by the industrial users:

$$\frac{dR}{dt} = r(1 - R) - E \tag{1.3}$$

1.3.4 Domestic User Well-being Function and Population Dynamics

Changes to the resource state, employment opportunities, and wages in turn affect the community wellbeing, which depends both on the resource to fulfill basic needs and on employment as a source of income. Resource access and economic security interact to determine the well-being of communities, for whom these issues tend to be linked (e.g. paying for alternative water sources or high water bills can be a significant economic burden). Community well-being is therefore a product of their resource access index, S, and their effective wage, or expected value wage, $W \cdot \frac{L}{U}$. The resource access index is a function of the proportion of the resource state and the maximum resource capacity. The effect of the resource state on community resource access is modeled as nonlinear, representing how large shortages and greatly degraded quality have a disproportionately large impact on well-being. The index ranges from 0 to 1, and aims to capture the diminishing marginal benefit of resource once a level of resource sufficient to satisfy basic needs is met:

$$S = \frac{1 - e^{-kR}}{1 - e^{-k}} \tag{1.4}$$

where k is a parameter for the resource access benefit relative to the proportion of remaining resource.

Individuals then decide whether to migrate out of the system based on their well-being relative to a constant outside-of-system well-being. Changes in population follow replicator dynamics, a model originating in evolutionary game theory that is commonly used to represent how individuals choose between options in a boundedly rational manner, imitating observed strategies that receive higher payoffs.(Cressman and Tao, 2014) The rate at which individuals switch between strategies – in this case the decision to stay within the system or migrate out – is proportional to the payoff difference between the options:

$$\frac{dU}{dt} = mU\left(SW \cdot \frac{L}{U} - p\right) \tag{1.5}$$

where p represents the well-being outside of the system and m represents the community's responsiveness to differences in well-being inside and outside of the system.

The results of the migration determine the labor available to industrial users.

1.3.5 Policies

These dynamics generate a rich set of feedbacks among industrial users, the community on which they rely for labor, and their shared resource, encapsulating the "self-organized" part of the system.

SESs, however, are part self-organized, and part designed.(J. M. Anderies, 2015) We implement the "designed" component of this system through regulation that aims to mitigate for myopic behavior by regulating industrial users' resource use. The policies influence industrial users by being incorporated as a cost in their profit function.

If implemented, the cost imposed by the policy is included as an additional term in the industrial users' profit function (Equation 1.1).

The fee is calculated as follows:

$$T(E) = \begin{cases} 0 & \text{if } E \leq C \\ f(E-C) & \text{if } E > C, \end{cases} \tag{1.6}$$

where f represents the fee amount per unit of extraction above the extraction threshold C.

1.3.6 Alignment Metric

The alignment of equity with resilience is calculated as follows:

$$\text{Alignment} = \frac{P(E|R) - P(E)}{1 - P(R)} \tag{1.7}$$

where $P(E|R)$ represents the proportion of the resilient region (within 95% of optimal resilience) that is also within 95% of optimal for equity, $P(E)$ represents the proportion of the whole colormap that is equitable, and $P(R)$ represents the proportion of the whole colormap that is resilient. Similarly, the alignment between resilience combined with profit and equity is calculated as follows:

$$\text{Alignment} = \frac{P(E|(R \wedge P)) - P(E)}{1 - P(R \wedge P)} \tag{1.8}$$

where $P(E|(R \wedge P))$represents the proportion of overlapping region between high resilience and high profit that also leads to high equity, and $P(R \wedge P)$ represents the proportion of the whole colormap that is in the overlap region between resilience and profit. Note that we use probability notation only for conciseness, and not to suggest that these proportions are equivalent to the probabilities of these outcomes.

1.3.7 Parameter Settings

Parameter values were held constant in all analyses (Supplementary Table 1). A negative substitution parameter in the industrial user production function was chosen to reflect limited substitutability between resource and labor, as is the case in agriculture, for example (Howitt et al., 2012). A constant is included in the revenue term to reflect the limit on non-labor and non-resource inputs to production (e.g. a maximum area of land available), leading to an asymptotic production function. The remaining parameters are chosen to satisfy the assumption that 1) there are two possible equilibria, and 2) that implementing a policy limiting extraction can increase the resilience (see Supplementary Information Parameter Values section for how these parameter ranges were determined).

1.3.8 System Solution

Analytical stability analysis of the system is not possible, so the system is solved numerically using Euler's method with a step size of 0.08. The system is considered to have reached equilibrium when the maximum of the Euclidean distances between the current state of the system and the system state in any of the previous ten steps is less than a set tolerance. The code used to solve the system and produce all figures can be found at: https://github.com/njmolla/SES-equity-resilience

1.3.9 Policy Outcomes

100 initial conditions are sampled throughout the state space using Latin Hypercube Sampling for each policy, or combination of cap and fee amount (see Supplementary Information Figure Details section for more information about Figures 1 and 2). The equilibrium industrial profits and wellbeing, calculated as the product of the individual wellbeing and population ($W \times S \times L$), are averaged over all of the trajectories. The resilience is calculated as the proportion of the initial conditions leading to the sustainable equilibrium. For the

state variables that are not naturally bounded (the wage and population), the sampling bounds on the initial conditionsare chosen to encompass both attractors as well as almost the entirety of the trajectories sampled within the bounds (see Supplementary Figure 4). Thus, the chosen region represents the “realistic” range of states within the system .

The range of policy thresholds was chosen to encompass the full range of thresholds for which the policy has an impact; higher thresholds have exactly the same effect as no policy at all. The range of policy parameters was chosen to incorporate the region for which changing the fee amount changes industrial user behavior. Sufficiently high fees function as a cap, where the extractors never pay the amount, and the system does not respond to further fee increases.

This model formulation now allows us to analyze the mechanism under which the system fails to sustain industrial profitability and community well-being, how regulating extraction can perturb these dynamics, and its implications for resilience and equity.

1.4 Results and Discussion

1.4.1 System Dynamics and Equilibria

The model dynamics generate two different long-term system outcomes, or equilibria: a ‘collapse’ outcome involving a failure of the social and economic systems, and a sustainable outcome, in which the system indefinitely supports productivity and community livelihoods (Figures 1.2 and 1.3). The collapse outcome is triggered by industry depleting the resource to a level where they can no longer profitably extract at the same time that a lack of resource access has caused the population to decline, eventually setting the system on an irreversible course. While the resource recovers when industry is not productive, the population does not; the lack of productivity leads to a self-reinforcing feedback loop with out-migration, making future productivity impossible as well. This mechanism is similar to the concept of runaway dispersal that has been documented in social species, in which density-dependent copying, as occurs in replicator dynamics, leads to nonlinear and irreversible changes in population (Oro, 2020). The dynamics of the rapid initial growth followed by collapse is also reminiscent of the "boom-bust" dynamics seen in many case studies of RBCs, particularly throughout Northern Canada, where industry collapse, in part due to over-exploitation of the renewable resource base, and out-migration threaten the future of these communities (Tsenkova and Youssef, 2014; Bilsborrow, 2002; Dolan et al., 2005). The sustainable equilibrium, in contrast, hinges on remaining within the region of the state space in which self-balancing dynamics dominate, particularly in terms of maintaining enough economic opportunity and resource access to support community wellbeing. Figure 1.2 shows an example of a model run in which the introduction of a policy to regulate industrial users, can intervene in whether a given set of initial conditions leads to collapse by modulating the initial resource decline.

The region of the state space that leads to the sustainable equilibrium (Figure 1.3) represents the basin of attraction for the sustainable equilibrium. The (ecological) resilience of the system is the size of the basin of attraction, measured as the proportion of sampled trajectories that lead to the sustainable equilibrium (see Methods for more details). Conceptually, this represents the extent to which the system could be perturbed from the trajectories shown, such as by exogenous shocks like drought, while retaining long-term sustainability. This measure of resilience is not the resilience of the resource, nor any other individual component of the system – and in fact leads to a lower equilibrium resource level than the collapse equilibrium. Rather it represents the resilience of the system's functioning as a resource-based community that sustains an industry and community users. The introduction of a policy expands the basin of attraction (Figure 1.3), increasing the ecological resilience of the RBC. The next part of the analysis focuses on understanding the equity implications of the policy within the regime in which the policy can increase resilience (see Supplementary Figures 1 and 2 and Supplementary Table 2).

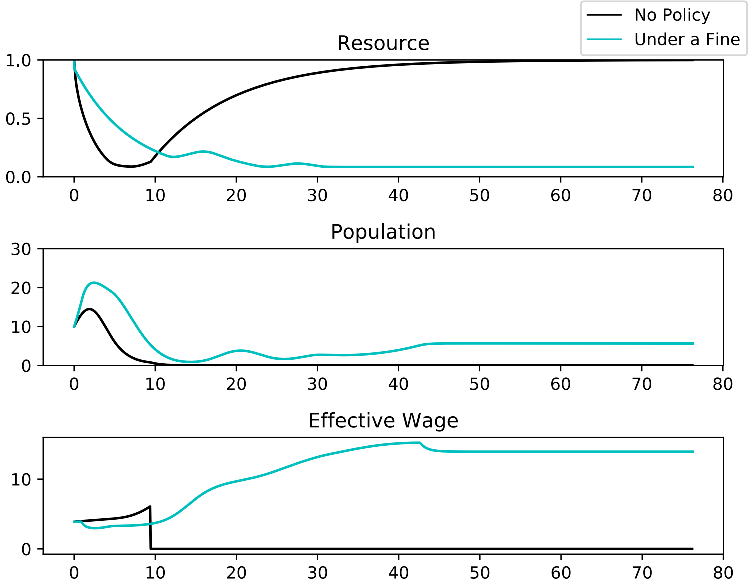


Figure 1.2: An example time series of resource, population, and effective wage with no policy (black), and with a fine implemented (cyan). The effective wage is the wage scaled by the proportion of available labor that is employed.

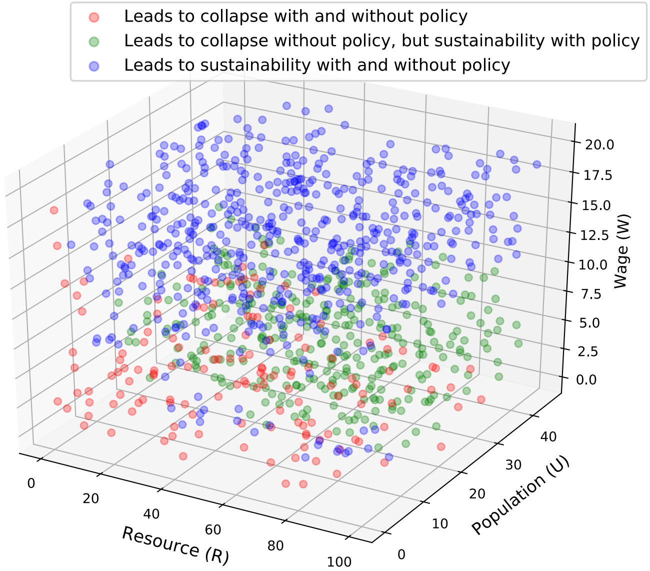


Figure 1.3: Scatterplots of the phase space color coded by their equilibrium condition under no policy and under the optimal fine for increasing resilience (a cap of 0.05 and a fine of 125). 1000 initial conditions are sampled throughout the state space using Latin Hypercube Sampling (LHS). In this example, the proportion of trajectories that are attracted to the sustainable equilibrium, or the resilience, changes from about 53% to 99% under the policy.

1.4.2 Governance Challenges and Tradeoffs

While regulating industrial users promotes the resilience of the system, it also changes the location of the sustainable equilibrium (see Supplementary Figure 5), which has important implications for equity. The desirability of outcomes for industry and community are represented by their profit and well-being, respectively. The community wellbeing is measured as the product of the resource access, effective wage, and population. We define equitable policies as those leading to near-optimal well-being for the community (shown in Figure 4), the most vulnerable group in the system. The alignment of equity with resilience in the policy space is calculated as the difference in the proportion of the high resilience region that is equitable and the proportion of the policy space generally that is equitable, or in other words, the gain in the proportion of equitable policies if focusing solely on resilience (see Methods for a mathematical definition). This metric is normalized such that it will range from -1 to 1, with 1 representing perfect alignment (ie. the regions of equity and resilience are exactly the same), -1 representing objectives that are completely opposed, and 0 representing a lack of correlation, positive or negative, between the two objectives.

The definition of resilience and equity requires that they be at least somewhat aligned at equilibrium, since a high wellbeing is not possible in a collapse state. However, even at equilibrium, point (c) in Figure 1.4 reveals that resilience, while a necessary condition for equity, does not guarantee it. This difference in the policies that lead to high resilience and high equity is important if decision-makers are focused only on resilience or have limited knowledge of the system response and therefore cannot accurately determine where the equitable region is.

Distinguishing between resilience and equity becomes more important when considering the transient effects of different policies (Figure 1.4). While resilience as defined applies only to equilibrium outcomes, the response surface for equity changes over time such that achieving resilience becomes more aligned with equity as the system approaches equilibrium. This dynamic is even more pronounced when considering the common objective of profit in conjunction with high resilience. The combination of resilience and high profit actually conflicts with achieving equity (negative values of alignment) in earlier time periods. Equity therefore warrants standalone analysis, especially when considering transient effects. While the fact that at equilibrium the combination of resilience and high profit does not directly conflict with equity may seem encouraging, even short-term tradeoffs are important to consider in practice, particularly for systems in which variables like the resource or population are slow drivers. Resilience being insufficient for predicting equity as well as these temporal dynamics hold when considering different thresholds, policy types, and parameters (see Supplementary Figures 3, 7, and 8).

The goal of this analysis is not to advocate any particular timescale of analysis or to optimize policy parameters, but to understand how incorporating power disparities in our model formulation and considering equity as an objective complicates the objective of building resilience in ways that are otherwise difficult to anticipate. This analysis allows us to look beyond simple constrained optimization and other standard approaches to understand both the transient and long-term, non-trivial interactions between resilience and equity, that arise from the system-level dynamics of migration, resource extraction, and wage labor, in systems fraught with power asymmetries and uncertainty.

1.5 Conclusion

What, then, do these findings mean for broader meanings of resilience in RBCs? As with equity, community resilience may be related to ecological resilience since a stable population can help foster the community cohesiveness and connectivity needed to build community resilience according to the social disruption hypothesis (Berkes and Ross, 2013; Deacon, 2015). However, since community resilience is process-based, transient effects on community wellbeing and equity are important factors in ultimately determining community resilience.

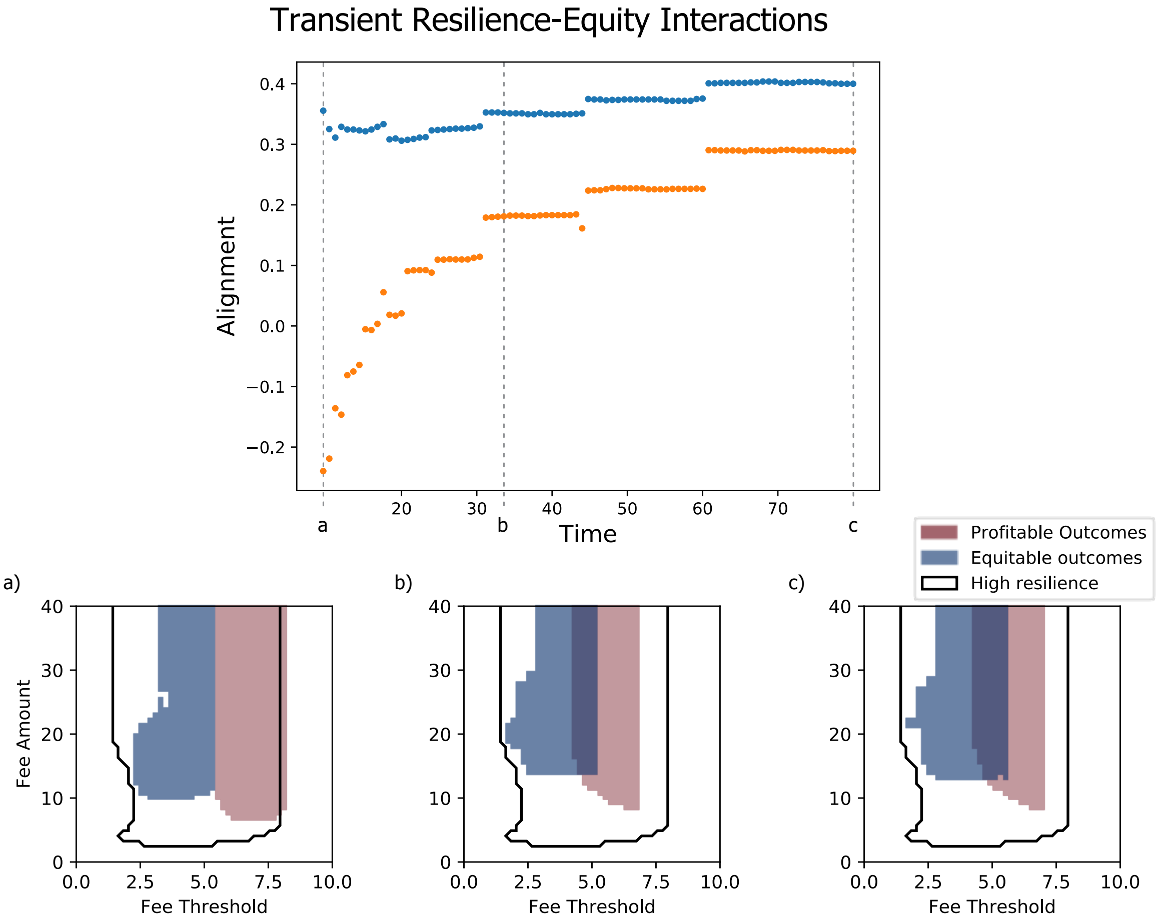


Figure 1.4: The alignment of high equity with high resilience, as well as of high equity with a combination of high profit and resilience, at different points in time. The alignment is measured as the gain in the proportion of policies with high equity if restricted to the high resilience region compared to the proportion of policies with high equity in the policy space as a whole. (a), (b), and (c) show the regions of the policy parameter space that generate near-optimal (within 5%) industrial profits (in red), community well-being (in blue), and resilience (within the boundary) used in the alignment calculation. See Supplementary Figure 6 for colormaps of the objectives at equilibrium.

On the flip side, community resilience may be a mitigating factor in the dynamics modeled here, since the model is limited in capturing how communities adapt and evolve to changing resource access conditions rather than having a fixed relationship with a resource. In addition, there are other scales of analysis, temporal and spatial, on which to consider resilience-equity interactions. Increased ecological resilience on the scale of individual communities as studied here, by maintaining an inherently inflexible and inequitable system, may mean reduced social-ecological resilience on a broader scale, as is the case with economies that rely on extractive industries (ie. the "resource curse") (Berkes, Folke, and Colding, 1998; Freudenburg, 1992).

Many SESs are characterized by complex social relationships among users, most notably power asymmetries, that have important implications for analyses of the collective action problem. This study focuses on RBCs as a quintessential example of a system with such disparities that exists throughout the world and has been underrepresented in the SES and common pool resource literature. The results, in addition to revealing a mode of system collapse that is not foreseeable without considering long-term dynamics of migration and extraction, reveals a misalignment between the commonly conflated objectives of resilience and equity. These results hinge on the disparity in the industry and the community's access to capital and technology for extracting or accessing the resource, and the community receiving limited benefits from extraction. This disparity in who benefits from extraction means that gains in system resilience enabling sustained production are not always aligned with gains in community wellbeing, as might be the case in the more homogeneous smallholder systems more commonly studied in the common-pool resource literature (Ostrom, 1999; J. Anderies, Janssen, and Schlager, 2016). This study additionally assumes a renewable resource with constant regeneration. However, the fact that a collapse can still occur means this result would hold even if modeling a resource for which a low resource level leads to a low regeneration rate, as is the case with many biological resources. The model also still offers insight for RBCs based on extraction of non-renewable resources, such as fossil fuels, if considering how communities rely on renewable natural capital, like water, that also tends to be degraded by extractive industries. Understanding the transient effects on equity also becomes crucial for systems in which collapse is the only possible equilibrium. While the concept of ecological resilience based on multiple equilibria for the resource state would not apply, the transient wellbeing would be an important driver of community development after the resource collapses. Finally, applying this model for real-world prediction and policy design would require identifying parameter values for a particular case study, which is an area for future work. However, the main contribution of this analysis is disentangling ecological resilience from its normative associations, and eventually towards developing theory around when building resilience of a particular system is desirable from an equity perspective, as opposed to more transformative changes.

This study represents a first step towards developing models that better capture the social complexity of SESs to understand the processes driving systems to collapse and the tradeoffs inherent in inequitable systems. While this system is characterized by unequal distributions of the resource, capital, and political power, our analysis focuses mainly on how differing control over and access to resources influences social-ecological outcomes. Future work should explore how other manifestations of power asymmetries, such as in access to institutions and political processes, influence social-ecological outcomes, with the recognition that the governance processes represented as exogenous in this model are themselves a commons dilemma (J. Anderies, Janssen, and Ostrom, 2004). Understanding the dynamics of these systems will only become more important as industrialization and globalization generate greater inequity within resource systems, and along with climate change, leave increasing numbers of rural communities to grapple with the threat of economic decline and environmental degradation (Swick, 2014).

1.6 Appendix

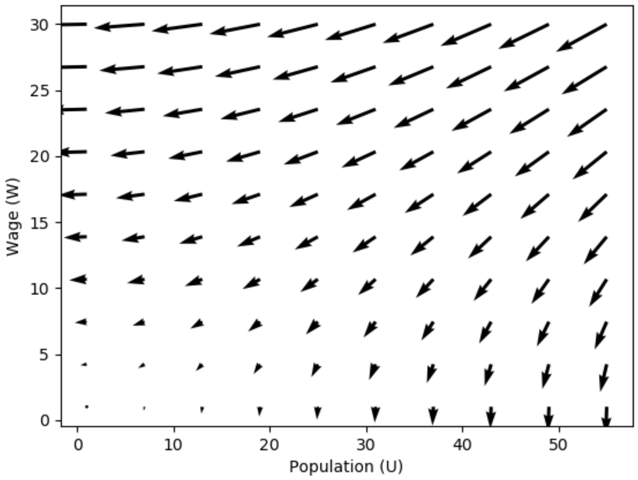
Supplementary Methods

Model Parameters

Symbol	Definition	Value
r	Resource regeneration rate	0.1
a	Industrial user revenue threshold	1000
b_1	Resource share parameter in production function	1
b_2	Labor share parameter in production function	1
q	Substitution parameter	-0.5
c	Extraction cost	0.05
d	Fixed cost parameter in profit function	100
k	Benefit of resource access exponential parameter	2
g	Rate at which wage increases with marginal benefit of additional labor	0.01
h	Rate at which wage declines with excess labor	0.06
m	Responsiveness of domestic users to payoff difference	0.8
p	Out-of-system payoff for domestic users	3

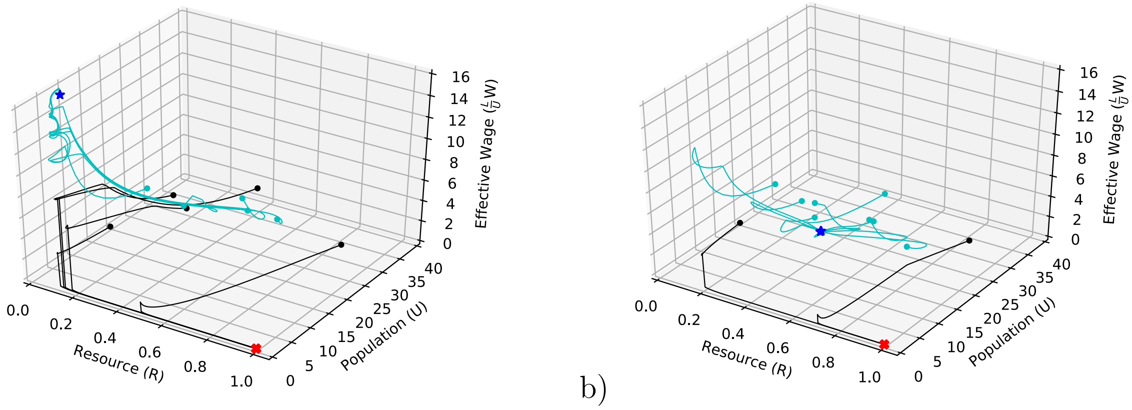
Supplementary Table 1.1: Model Parameter Definitions and Settings

State Space Bounds



Supplementary Figure 1.5: Quiver Plot of a 2d Slice of the State Space (with $R = 1$). Demonstrates that trajectories within the bounds chosen will largely stay within the bounds, ensuring that the region in which the interesting behavior of the model occurs is included.

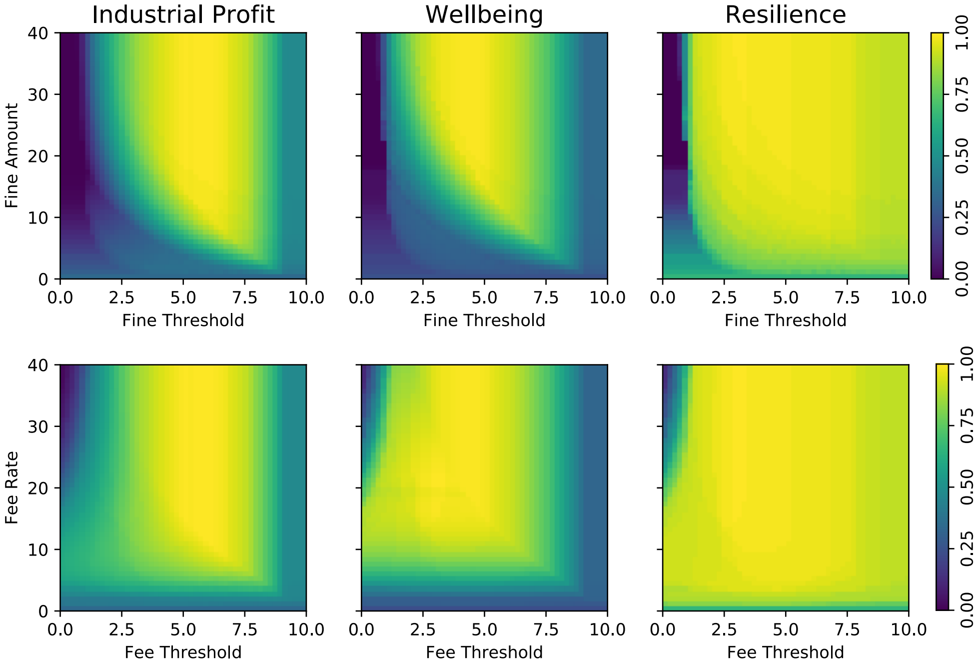
Supplementary Figures and Tables



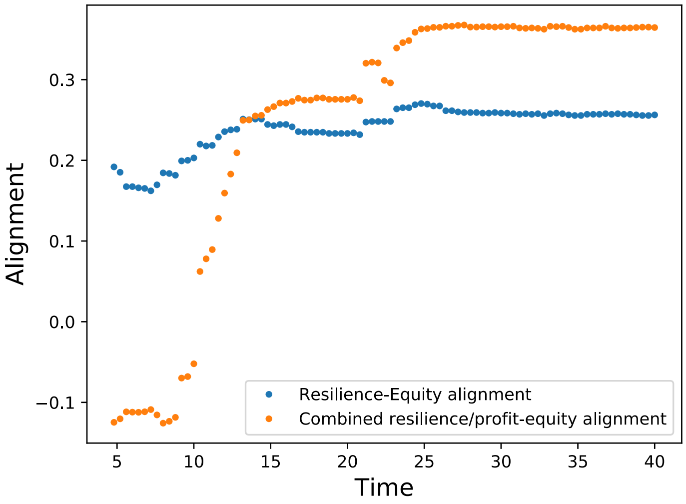
a)

b)

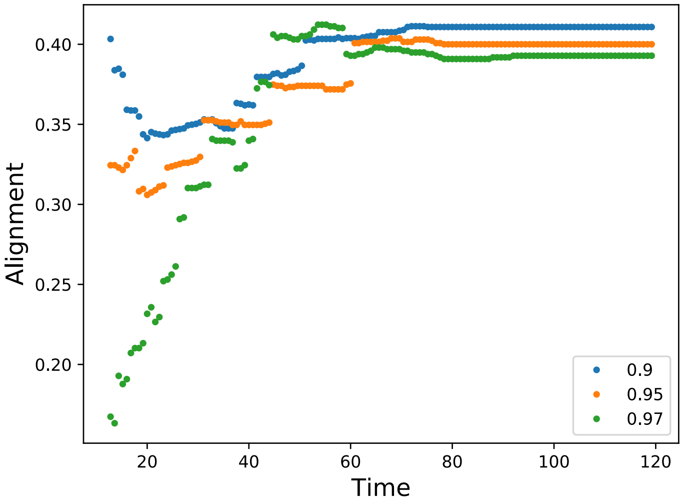
Supplementary Figure 1.6: Phase portrait under a) no policy and b) a fine. Trajectories in black lead to the collapse equilibrium state (red 'x') while cyan trajectories lead to the sustainable equilibrium state (blue star). 10 initial points are sampled throughout the state space using Latin Hypercube Sampling (LHS). Figure 3b uses a cap of 5 and a fine of 125.



Supplementary Figure 1.7: Colormaps of average equilibrium industrial profits and population, and the resilience (measured as proportion of sampled initial conditions that lead to the sustainable equilibrium) under varying fee parameters. 100 initial conditions are sampled over R from 0 to 1, U from 0 to 45, and W from 0 to 20 using LHS for each policy (combination of threshold and fine amount or fee rate).



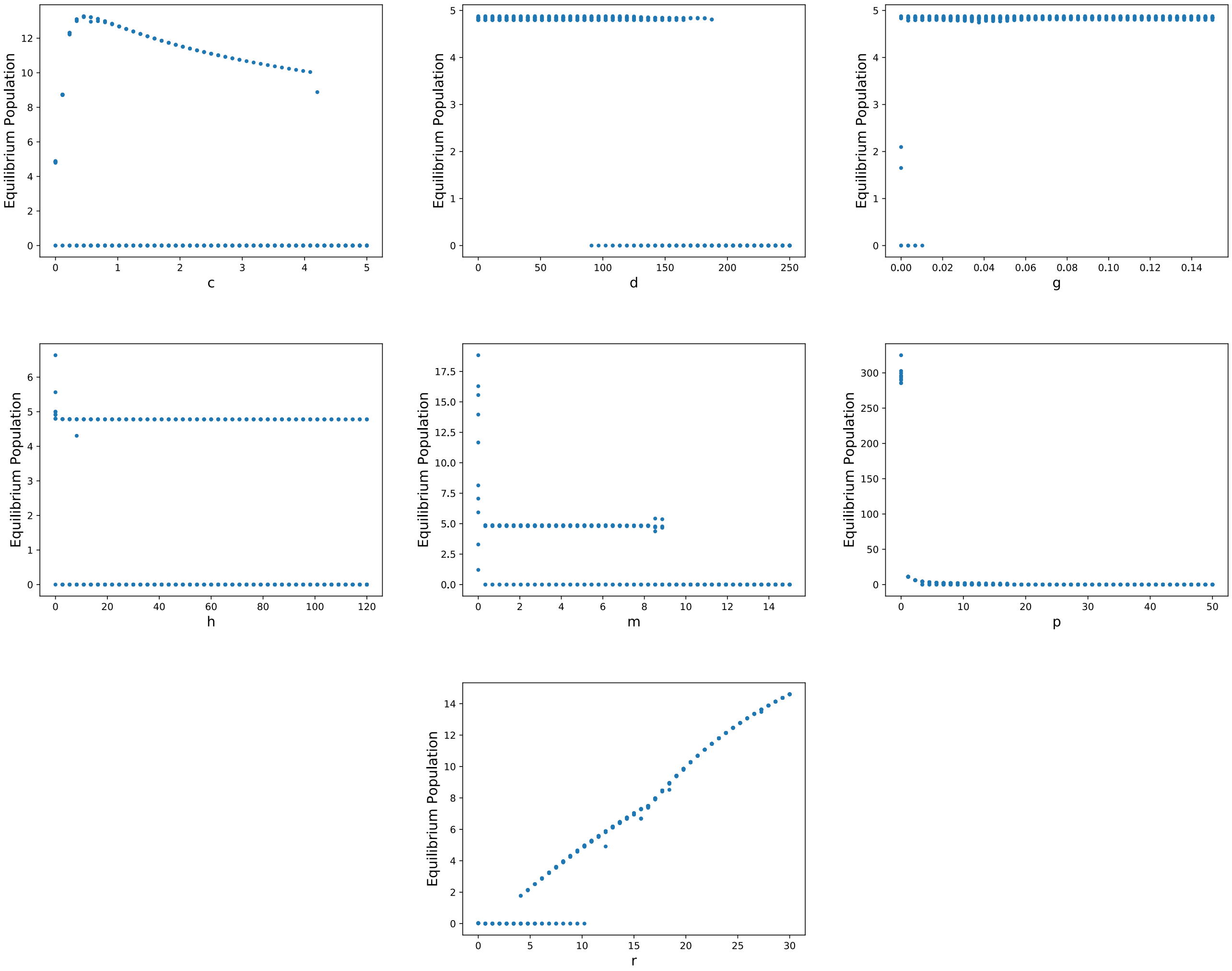
Supplementary Figure 1.8: Resilience-Equity Alignment for a Cap with a Fine.



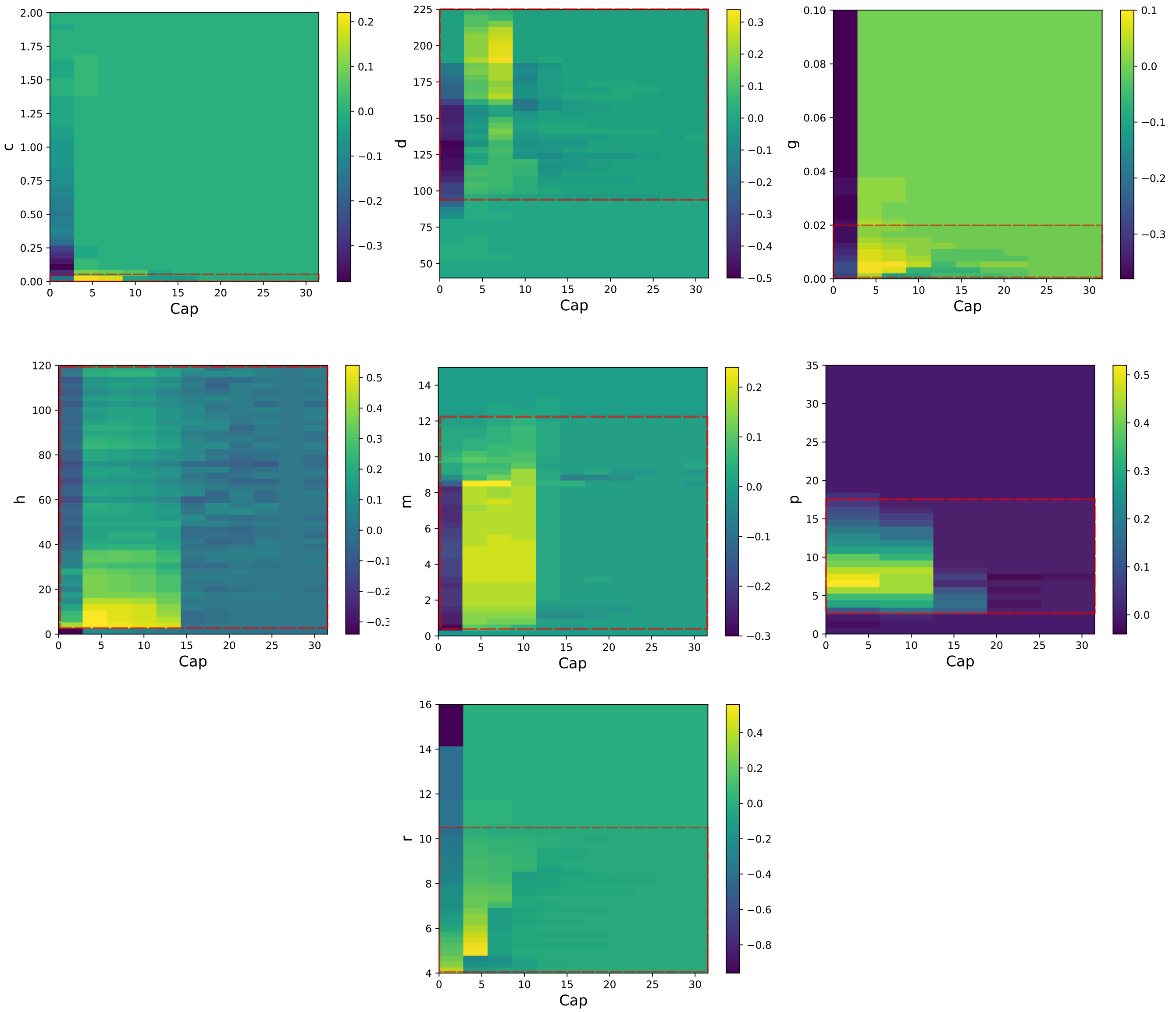
Supplementary Figure 1.9: Resilience-Equity Alignment for a Fee at different thresholds.

Symbol	**Definition**	**Value**	**Range**
r	Resource regeneration rate	0.1	0.015-0.105
c	Extraction cost	0.05	0-0.05
d	Fixed cost parameter in profit function	100	95-225
g	Rate at which wage increases with marginal benefit of additional labor	0.01	0-0.02
h	Rate at which wage declines with excess labor	0.06	0-120
m	Responsiveness of domestic users to payoff difference	0.8	0.3-12.3
p	Out-of-system payoff for domestic users	3	2.7-18

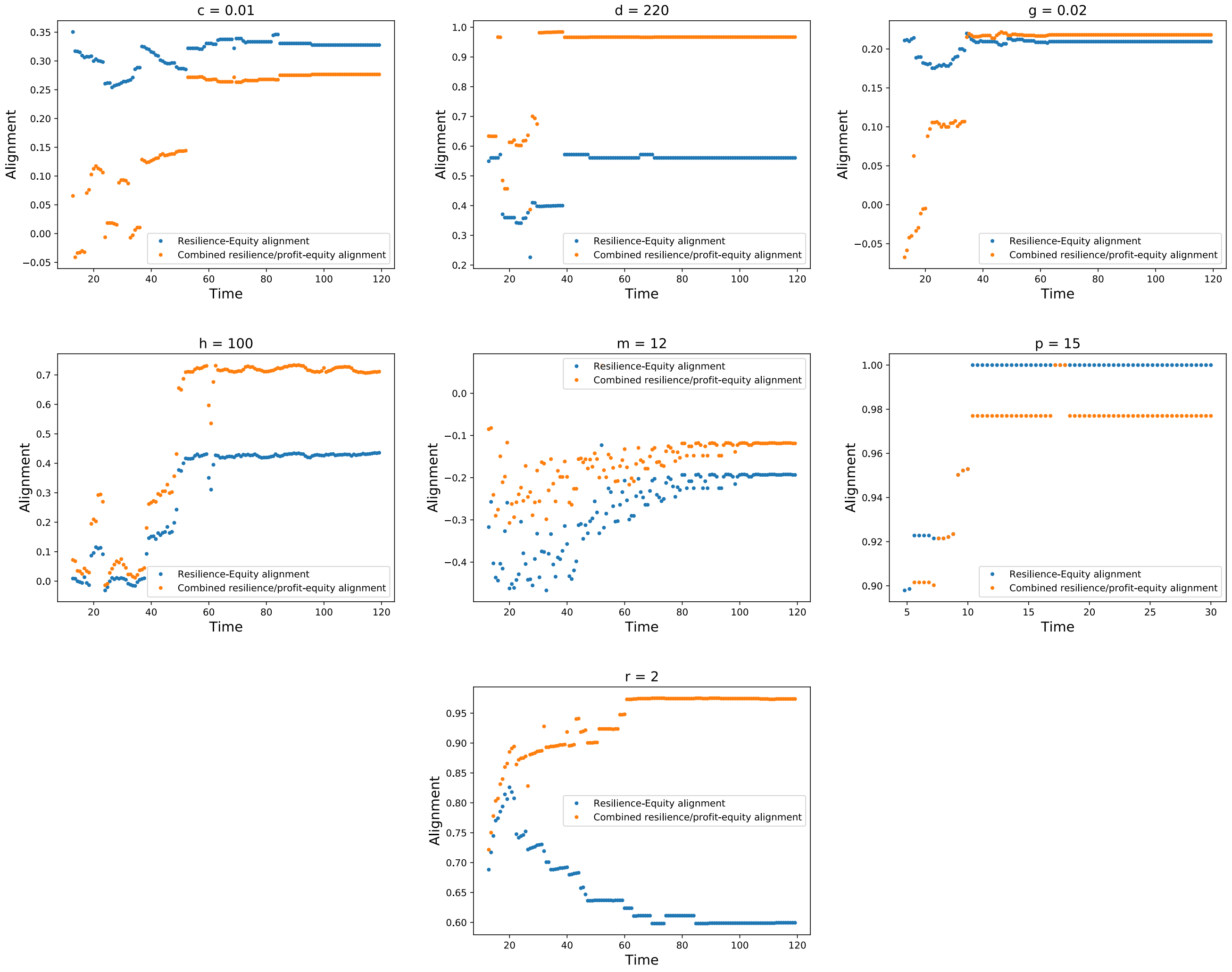
Supplementary Table 1.2: Parameter ranges for parameter experiments (see below). Determined based on the ranges over all of the caps in Supplementary Figure 2 that lead to an increase in resilience by at least 0.2 (shown in the boxed region on each subplot).



Supplementary Figure 1.10: One-dimensional bifurcation diagrams. Each point represents the equilibrium value for 10 trajectories, sampled using Latin Hypercube Sampling. Other parameters are held fixed (Table 1 values).



Supplementary Figure 1.11: Parameter ranges (in red boxed region) in which regulating industrial user extraction increases resilience. Colormap values represent the difference in resilience relative to no policy. Figures produced by sampling 50 points using Latin Hypercube Sampling and using a fee of 500 (which is sufficiently high as to always affect extraction decisions) for each parameter value and cap.



Supplementary Figure 1.12: The alignment between high resilience and high equity, as well as between high profit in conjunction with high resilience and equity, at different points in time. All parameters other than the one varied are held fixed, and 80 trajectories were sampled for each point in the policy space. The threshold for each figure is 95% of optimal, except for r, h, and m, for which the thresholds of 20%, 65%, and 45% were used because they were the highest thresholds at which there were significant overlapping regions.

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Chapter 2

A Dynamical Systems Approach to Understanding the Stability of Environmental Governance[1]

2.1 Abstract

The ability to adapt to social and environmental change is an increasingly critical feature of environmental governance. Yet, an understanding of how specific features of governance systems influence how they respond to change is still limited. Here we focus on how system features like diversity, heterogeneity and connectedness impact stability, which indicates the system's capacity to recover from perturbations. Through a framework that combines agent-based modeling with generalized dynamical systems modeling, we model the stability of thousands of governance structures consisting of groups of resource users and non-government organizations interacting strategically with the decision centers that mediate their access to a shared resource. Stabilizing factors include greater effort dedicated to venue shopping,

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and a greater fraction of non-government organizations in the system. Destabilizing factors include greater heterogeneity among actors, a greater diversity of decision centers, and greater interdependence between actors. The results suggest that while complexity tends to be destabilizing, there are mitigating factors that may help balance adaptivity and stability in complex governance. This study demonstrates the potential in applying the insights of complex systems theory to managing complex and highly uncertain human-natural systems in the face of rapid social and environmental change.

2.2 Introduction

Social-ecological outcomes such as sustainability, resilience, and equity, are ultimately the product of a complex set of interactions among networks of autonomous actors self-organizing to address interconnected issues – or in short, governance (Carlisle and Gruby, 2019; Klijn and Snellen, 2009; Koppenjan and Klijn, 2004; Pahl-Wostl, 2009; Stephan, Marshall, and M. McGinnis, 2019). A diverse literature has emerged to explore governance as a complex system, which breaks with the traditional notion of governance as a linear and centrally managed process of planning and execution (Buuren, Boons, and Teisman, 2012; Klijn and Snellen, 2009; Pahl-Wostl, 2009). Instead, complex governance emphasizes interactions among mutually dependent actors, a structure that is at least partially self-organized rather than externally imposed (Pahl-Wostl, 2009; Lubell and Morrison, 2021; Stephan, Marshall, and M. McGinnis, 2019), and cross-scale feedbacks. Evolution in the structure and function of governance is understood to be the norm rather than the exception (Thiel, Pacheco-Vega, and Baldwin, 2019). This conceptualization of governance has been explored from various perspectives, including adaptive governance (Folke, Hahn, et al., 2005), collaborative governance (Ansell and Gash, 2008; Ansell, 2012; Gerlak, Heikkila, and Lubell, 2012), multi-level governance (Bache, Bartle, and Flinders, 2016; Hooghe and Marks, 2002; Liesbet and Gary, 2003; Newig and Fritsch, 2009), and polycentric governance (V. Ostrom, Tiebout, and Warren, 1961; E. Ostrom, 2010; M. D. McGinnis and E. Ostrom, 2012; Carlisle and Gruby, 2019).

A central question regarding complex governance is how its structure impacts its function. For example, multiple autonomous but interdependent decision centers, a defining feature of polycentric governance (V. Ostrom, Tiebout, and Warren, 1961; E. Ostrom, 2010; M. D. McGinnis and E. Ostrom, 2012), has been ascribed numerous benefits, such as effective production and provision of diverse public goods (V. Ostrom, Tiebout, and Warren, 1961; Pahl-Wostl, 2009), and greater ability to adapt to a changing environment (Folke, Hahn, et al., 2005; Bixler et al., 2016; Pahl-Wostl, 2009; da Silveira and Richards, 2013). In Ostrom's institutional design principles, multi-level, nested governance is associated with robust institutions for maintaining the commons (E. Ostrom, 1990). A greater diversity of stakeholders is thought to yield better environmental outcomes (Newig and Fritsch, 2009) and more flexible and responsive governance processes that are better able to navigate external complexity and change (Craig et al., 2017; Koppenjan and Klijn, 2004). However, much of the focus has been on associating system outcomes with collaborative or polycentric governance as a whole rather than with specific factors, such as diversity in institutions and decision centers, heterogeneity among stakeholders, or connectivity among policy actors. This is perhaps because case studies make it challenging to independently test the effect of these different features. Understanding how these features relate to different governance outcomes with greater specificity is important in diagnosing cases in which the expected benefits associated with complex governance do not materialize (Carlisle and Gruby, 2019; M. D. McGinnis and E. Ostrom, 2012). This study disentangles the effect of these different features of complex governance systems by developing a modeling approach that allows for generating and analyzing the system-level outcomes associated with ensembles of resource governance systems with different configurations.

Given that constant change is a central feature of complex systems, a system-level outcome of particular interest is stability. Mathematically, a steady state with local asymptotic stability is one for which trajectories near the steady state will approach the steady state. Conceptually, local asymptotic stability, hereafter referred to as stability, is an indication of the system's ability to retain its structure and function in the face of local perturbations in the variables controlled by the governance system (Guckenheimer and Holmes, 1983). In addition to being well-defined mathematically, stability is considered an important feature in the context of governance systems, if not a universally desirable one. On the one hand, stability in governance arrangements allows people and organizations to learn about one another, experiment, and make long-term investments (Craig et al., 2017; Pahl-Wostl, 2009). It allows for the accumulation of wellbeing and resources when external change is slow and predictable, and reduces transaction costs and increases returns from cooperation (D. C. North, 1990; D. North, 2005). On the other hand, stability can correspond to rigidity, in which governance systems fail to respond to internal changes (Stephen Carpenter and Brock, 2008; Craig et al., 2017). Stability also serves as a prerequisite for ecological resilience, which emphasizes the ability of a system to absorb perturbations without changing structurally (Holling, 1973), but may conflict with adaptive capacity, which emphasizes transformation (Folke, Steve Carpenter, et al., 2002; Stephen Carpenter and Brock, 2008). Understanding stabilizing factors in resource governance systems therefore also gives insight into their resilience and adaptive capacity.

While the question of how features of governance correspond to stability has not yet been addressed with much specificity or precision, the factors that lead to stability in complex systems has long been debated in the complexity literature, particularly in the context of ecosystems. For example, increased complexity in food webs, in terms of species diversity and their connectivity, has been shown to lead to decreased robustness (May, 1972; May, Levin, and Sugihara, 2008), while certain predator-prey ratios have been found to be stabilizing (Bambach, Knoll, and Sepkoski, 2002). Therefore, in addition to a better understanding of complex governance, this study provides insight into whether the principles for stability that have been discovered in other complex systems generalize to social-ecological systems.

2.3 Methods

This study focuses on common-pool resource governance with a resource that is subtractible, such as a groundwater aquifer, though the model could be parameterized for public goods instead. The overall modeling approach consists of defining the structure of the dynamical system in terms the different components of the governance system and their interactions, using generalized modeling to analyze stability without specifying functional forms. This method is particularly suited to gaining general insights about a system despite the large uncertainties that may exist, particularly in social systems, by allowing for studying an ensemble containing several thousand realizations of variants of the system structure. Computing the stability of the diverse system realizations in the ensemble thus allows us to identify underlying principles for stability.

The modeling framework consists of state variables representing the state of the shared resource and the organizational capacity of three types of entities: 1) resource user organizations or interest groups, which directly impact or are impacted by the resource state, and can represent both extractive and non-extractive users, 2) non-government organizations, which do not directly impact and are not directly impacted by the resource state but still have interests in the system (e.g. nonprofits, advocacy and education groups not directly tied to a particular resource use), and 3) decision centers, which have the ability to directly mediate resource users' interactions with the resource. Organizational capacity refers to resources like volunteer or staff labor, access to legal, technical, or administrative expertise, funds, or grassroots engagment. Resource users and non-government organizations will be referred to collectively as "actors" since they have an inherent stake in the system and are being modeled as strategic and self-organizing agents.

This model focuses on the processes that take place among the stakeholders themselves, such as collaboration and undermining, resistance and support, and lobbying (Table 2.1). This bottom-up perspective is chosen because of the under-representation of actors' agency in making and influencing decisions and pursuing their goals in the polycentric governance literature, which tends to focus solely on structure and exclude entities that lack the authority to create policies, though this is changing with concepts like institutional navigation (Lubell and Morrison, 2021), commoning (Dobbin, 2021; Villamayor-Tomas and García-López, 2018), and the sustainability transitions literature, which emphasize actors and the dynamic power relations among them as a driving force behind governance transitions (Avelino and Wittmayer, 2016). Modeling actors' ability to influence the effectiveness of policies or the capacity of other actors or decision centers to fulfill their missions captures the informal arenas and resistance of various sorts that can be pivotal in determining outcomes in resource governance, especially where state capacity and coherence is lacking (McCarthy, 2002). A complex systems approach is therefore complementary to existing social theories on how often informal interactions among different types of actors drive change in governance systems. The next few sections will outline the processes that are modeled for each type of state variable.

Process	**Target**	**Drivers**	**Example Parameters**
Resource Natural Gain/Loss	Resource state	Resource state	Sensitivity of natural gain to current resource state
Recruitment or External Support/Attrition	Actor or Decision Center capacity	Actor or Decision Center capacity	Sensitivity of capacity gain to current capacity
Extraction/Access	Resource	Policies supporting or reducing extraction, Actors' policy support/resistance	Share of extraction by each user, sensitivity of extraction/access to current state
Policies supporting or reducing extraction	Extraction	Decision center capacity, Actors' policy support/resistance	Sensitivity of extraction to policy
Actor Policy Support/Resistance	Policies supporting or reducing extraction	Actor capacity, Actor strategy	Sensitivity of policy effectiveness to Actor efforts to resist/support it
Collaboration/ Undermining	Actor capacity	Actor capacity, Actor strategy	Share of actor capacity gain from collaborating with others, sensitivity of actor capacity to efforts to support them
Decision Center Support/Resistance	Decision Center capacity	Decision center capacity, Actor capacity, Actor strategy	Sensitivity of Decision Center to efforts to support them

Table 2.1: Summary of modeled processes, the variables or sub-processes linked through these processes, and example scale or exponent parameters associated with the processes. The scale parameters represent the significance of certain processes in driving changes to the state variables, while the exponent parameters represent the sensitivity of the processes to the drivers. The last three processes are driven in part by actors' strategies, which are represented though how they allocate their capacity to maximize their resource access.

Example Parameter	Type	Meaning
$\frac{\sum_n E_n}{R}$	Scale	Extraction rate of resource (i.e. inverse of characteristic time scale of resource)
$\frac{E_1}{E_1 + E_2}$	Scale	Share of total extraction extracted by Resource User1
$\frac{\partial E_1}{\partial R}$	Exponent	Sensitivity of Resource User1 's extraction to resource level

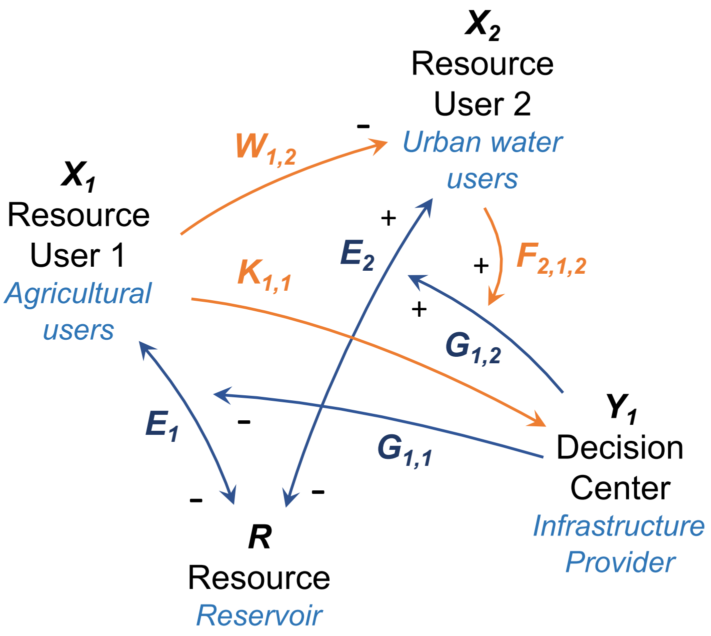

Figure 2.1: Example System Diagram. The nodes (R, X_1, X_2, and Y_1) are the state variables in the model, while the linkages represent functions (in blue) or parameters (orange) describing how the variables interact. In this example water governance system, there are two types of water users, agricultural users and urban users, withdrawing water from a reservoir. The governance intervention $G_{1,1}$ in this example can be interpreted as infrastructure managed by the infrastructure provider, or Decision Center, that delivers water to the city, supporting urban extraction while reducing agricultural extraction. The orange linkages represent possible Nash Equilibrium strategies that may result from this setup. In this example, urban users allocate all of their effort to supporting the infrastructure that allows for their extraction ($F_{2,1,2}$), while agricultural users split their effort between undermining the organizational capacity of urban users ($W_{1,2}$) and of the Decision Center ($K_{1,1}$).

2.3.1 Resource

The dynamics of the resource R follows a differential equation of the form

$$\dot{R} = S(R) - \sum_n E_n(R, G_{1,n}, \dots, G_{M,n}),$$

where S represents the reproduction/recharge and E_n the rate of loss from extraction/exploitation by resource user n, which is itself a function of R and interventions (e.g. regulations, subsidies, infrastructure) $G_{m,n}$ by decision center m to either support or reduce each user's extraction. In the example system, S represents the natural net gain to the reservoir after natural inflows and outflows that are not delivered to any users, and E_1 the total amount that agricultural users are able to extract. The effect of the intervention

$$G_{m,n} = G_{m,n}(Y_m, F_{1,m,n}X_1, \dots, F_{N,m,n}X_N)$$

is then a function of the capacity of corresponding decision center and of efforts $F_{k,m,n}X_k$ by each actor k to influence policies or the enforcement of these policies (see the section on Actors' Strategies for more details). In Figure 2.1, $F_{1,2}$ is an example of such an effort that could represent urban users advocating for increasing the conveyance efficiency of the infrastructure delivering their water. These nested functions integrate the resource state, actors' ability to access the resource, decision centers' efforts to intervene in their access, and, in turn, actors' efforts to influence these interventions.

2.3.2 Resource Users

The resource users' organizational capacity X_n is modeled by

$$\begin{aligned}\dot{X}_n = {} & B_n(E_n(R, G_{1,n}, \dots, G_{M,n})) \\ & + Q_n(A_n(R, P_{1,n}, \dots, P_{M,n})) \\ & + \sum_k C^+_{k,n}(W^+_{k,n} X_k) - \sum_k C^-_{k,n}(W^-_{k,n} X_k) - L_n(X_n),\end{aligned}$$

where B_n represents user n's gain in capacity motivated by their ability to extract E_n. The function Q_n is the analogous gain in capacity based on their non-extractive access to the resource, A_n. Depending on how these relationships to the resource are parameterized, these gain terms can represent different responses to resource access. This gain can represent actors becoming more agitated due to lack of access to the resource, and thus more motivated to dedicate time and resources towards engaging with the institutions that determine their access. It can also represent actors becoming more invested in ensuring access to the resource as their use of the resource, and the value associated with it, increases. This parameter therefore encapsulates the importance of the resource to the users and the productivity of the system in determining their likelihood to self-organize, as described by Ostrom's social-ecological systems framework (E. Ostrom, 2009). The function $P_{m,n}$ is analogous to $G_{m,n}$, representing interventions in their resource access and similarly affected by actors' efforts $H_{k,m,n} X_k$.

$C^+_{k,n}$ represents their gain in capacity from collaboration with or support from other actors that may, for example, provide information or resources about the institutions affecting their resource access or help connect them to these institutions (Barnes and van Laerhoven, 2015). They experience loss in capacity based on other actors' efforts to undermine them ($C^-_{k,n}$), through, for example, intimidation, misinformation, or demobilizing messaging and framing ($W_{1,2}$ in Figure 2.1). Actors also experience a loss in capacity from attrition or turnover (L_n) due to a gradual loss in interest and participation among actors, or their switching attention to issues external to the model domain.

2.3.3 Non-Government Organizations

Non-government organizations includes non-profits, outreach, advocacy organizations, and other non-government organizations that typically are more public-facing and formal than resource user groups and may receive funding or grants from external actors (e.g. donations or grants). These organizations play an important role in fostering and supporting collective action (Dobbin, 2021; Barnes, van Laerhoven, and Driessen, 2016; Barnes and van Laerhoven, 2015). Non-government organizations are modeled similarly to resource users by an equation of the form

$$\dot{X}_n = U_n(X_n) + \sum_k C^+_{k,n}(W^+_{k,n}X_k) - \sum_k C^-_{k,n}(W^-_{k,n}X_k) - L_n(X_n),$$

where U_n represents a gain in capacity from external sources.

Like resource users, these organizations have an objective related to the resource and are strategic, but have a gain term based on their own capacity, which allows them to secure external support, and do not have a gain term dependent on the resource, reflecting their more established and less reactionary nature.

2.3.4 Decision Centers

Decision centers, which can also be thought of as public infrastructure providers or venues for decisionmaking, intervene in resource users' ability to extract or access the resource, whether through provision of infrastructure, funding, or regulation. Their capacity Y_m is modeled by

$$\dot{Y}_m = I^+_m(Y_m, K^+_{1,m}X_1, \ldots, K^+_{N,m}X_N) - I^-_m(Y_m, K^-_{1,m}X_1, \ldots, K^-_{N,m}X_N),$$

where I^+_m represents their gain in capacity and I^-_m represents their loss in capacity. Both of these terms are functions of a decision center's existing capacity as well as actors' efforts at venue shopping, in which actors attempt to move decision-making authority to venues that are more favorable to them. These efforts are represented by $K^+_{k,m}X_k$ for supporting a venue, and $K^-_{k,m}X_k$, to undermine a venue. $K_{1,1}$ in Figure 2.1, for example, may represent agricultural users' efforts to undermine the authority of the Infrastructure Provider to withdraw water to deliver to urban water users.

2.3.5 Generalized Modeling Approach to Computing Stability

In typical dynamical systems analysis, the functions in the equations above would then be assigned specific functional forms. However, generalized modeling is based on the recognition that computing steady states is computationally expensive, while determining stability around a given steady state is far less costly. Determining stability around a given steady state requires only the ability to parameterize the Jacobian, which is a linearization of the system at the steady state, and thus requires less information than specifying particular functional forms that would describe the system's evolution throughout its entire trajectory. Bypassing the need for functional forms is particularly useful in modeling social systems, where the functional forms of processes are difficult to quantify and highly uncertain. This approach allows for analyzing system with a great degree of generality and without the computational constraints involved in modeling many different specific dynamical systems, and has been used to analyze a wide variety of systems (Gross, Rudolf, et al., 2009; Gross and Feudel, 2006; Lade and Niiranen, 2017). Therefore, rather than assign specific functional forms and compute the steady state, the functions are normalized by the unknown steady state. For example, the normalized resource dynamics would be represented by

$$\dot{r} = \frac{S^*}{R^*}s(r) - \sum_n \frac{E^*_n}{R^*}e_n(r, g_{1,n}, \ldots, g_{M,n})$$

where S^*, R^*, etc. are the values of the corresponding functions or state variables at equilibrium, and s, x_k, etc. represent the normalized functions or state variables. The normalization leads to the introduction of unknown factors S^*/R^* and E^*_n/R^*. However, these factors are constants and are treated as parameters, namely scale parameters. Scale parameters denote the magnitude of fluxes, such as turnover rates or the relative importance of different processes, while (Figure 2.1). We define $\phi := S^*/R^* = \sum_n E_n^*/R^*$, which represents the overall turnover rate of the resource, and $\psi_n := (1/\phi)(E_n^*/R^*)$, which represents the fraction of losses by each particular extractor at the steady state. The normalized resource dynamics can then be written as

$$\dot{r} = \phi \left(s(r) - \sum_n \psi_n e_n(r, g_{1,n}, \ldots, g_{M,n}) \right).$$

An example of an entry of the Jacobian based on this equation can then be computed as

$$\frac{\partial \dot{r}}{\partial r} = \phi \left(\frac{\partial s}{\partial r} - \sum_n \psi_n \frac{\partial e_n}{\partial r} \right).$$

The derivatives $\partial s/\partial r$ and $\partial e_n/\partial r$ are unknowns that are also treated as parameters, namely exponent parameters. These parameters are an indication of the sensitivity of the growth rate and the extraction rate to the resource state, respectively. In general, exponent parameters indicate the non-linearity of a process at equilibrium. Once the Jacobian is parameterized, the stability can be determined by checking whether the real part of all eigenvalues is negative. Conceptually, this means that perturbations in the state variables close to the steady state will return to that steady state. Local stability therefore indicates that the system will return to a steady state under short-term shocks (e.g. a sudden change to an actor's political influence), but does not necessarily indicate how the system will respond to large perturbations from the steady state or long-term drivers that fundamentally change the system's functioning (e.g. altering how resource users benefit from or impact the resource).

A full derivation and description of all model parameters can be found in the Supplementary Methods.

2.3.6 Actors' Effort Allocation

Recognizing that actors in a governance system are strategic and self-organized, a quality that is unique among the complex systems for which stability has been studied in a systematic manner, the generalized model is coupled with an agent-based modeling component. Each actor allocates their limited organizational capacity among different actions in order to maximize their equilibrium extraction or access to the resource (or for non-government organizations, the access or extraction of another actor). Their strategies are thus subject to the constraint:

$$\left(\sum_k \sum_m |F_{n,m,k}| + |H_{n,m,k}|\right) + \left(\sum_k |W_{n,k}|\right) + \left(\sum_m |K_{n,m}|\right) = 1$$

where F, H, W, and K represent the proportion of their effort dedicated to lobbying or otherwise directly supporting or resisting policies, collaborating with or undermining other actors, or directly influencing the capacity of a decision center, respectively. In Figure 2.1, for example, farmers divide their effort between undermining urban users' capacity ($W_{1,2}$) and undermining the capacity of the infrastructure provider that conveys water to urban users and away from farmers ($K_{1,1}$). The way actors allocate their effort among these actions is their strategy, which is calculated by finding a Nash equilibrium, in which no actor will want to unilaterally change their strategy.

While the generalized modeling approach means that the equilibrium extraction or access cannot be computed, the gradient of their extraction or access at the steady state can be calculated. As a simplified example of the method, take $\dot{X} = F(X, p)$, where p is a strategy parameter. To find how the steady state X^* depends on the strategy parameter, we can write this equation at the steady state with X^* as a function of p:

$$0 = F(X^*(p), p).$$

Taking the total derivative of both sides with respect to the strategy parameter gives

$$0 = \frac{\partial F}{\partial X}\frac{dX^*}{dp} + \frac{\partial F}{\partial p}.$$

We can then solve for:

$$\frac{dX^*}{dp} = -\left(\frac{\partial F}{\partial X}\right)^{-1}\frac{\partial F}{\partial p}.$$

In the full system, $\left(\frac{\partial F}{\partial X}\right)^{-1}$ is the inverse of the Jacobian. Once we know how the steady state depends on the strategy parameters, it is straightforward to compute how the extraction or access depends on each strategy parameter. See the Supplementary Methods for the full calculation of the gradient.

A Nash equilibrium is calculated by computing the gradient of the equilibrium extraction or resource access and performing iterative steps of gradient descent for each actor in turn until the strategies converge. While there is no guarantee of a Nash equilibrium since the strategy space is not necessarily convex, the strategy optimization process ensures that even if optimality is not reached, actors are behaving in ways that are self-consistent and compatible with their goal of increasing their resource access. Modeling actors as behaving reasonably, if not necessarily rationally, ensures that the systems that are analyzed are feasible governance systems.

The strategy parameters computed by the agent-based modeling component and the sampled generalized parameters collectively provide all of the information needed to compute the stability of the system. Varying the generalized modeling parameters, as well as meta-parameters defining the number of each type of state variable and how densely connected they are, allows for exploring the stability of a wide variety of topological configurations and feedbacks among actors and decision centers.

2.3.7 Experimental Methods

We investigate how three types of features of complex governance correspond with stability: 1) the scale and exponent parameters, to understand the importance of different processes and functional forms, as well as the importance of variance in these processes, representing, for example, heterogeneity in actors' response to resource access conditions, diversity in interventions, or inequity in actors' abilities to influence different governance processes, 2) the diversity of the system, indicated by the total number of actors and decision centers, and how densely connected they are, and 3) the relative number of decision centers and actors, to understand, for example, whether diverse stakeholder interests may have a different effect on stability than diversity in decision centers.

Parameter Correlations with Stability

To understand the impact of the scale and exponent parameters on stability, the size and composition of the system is held fixed and the scale and exponent parameters are sampled independently (see Supplementary Information for the parameter ranges). The small system has a total size of 5, with one extractor, one accessor, one non-resource user actor, and two decision centers. The large system has a total size of 15, with three of each type of resource user (extractors, accessors, and combined extractors and accessors), three non-resource user actors, and three decision centers. The decision center-resource user connectance (i.e., the probability that a given decision center will intervene in a particular resource user's extraction or access) is fixed at 0.4. The experiment consisted of 28,800 samples. The sample size was chosen to sufficiently narrow the 95% confidence intervals so that statistically significant correlations were distinguishable.

Stability is treated as a binary value. The correlation of a given parameter, x, averaged across all actors, with stability is given by

$$R = \frac{\sum_{i=1}^{v_s} x_{s,i} - \frac{v_s}{v}\sum_{i=1}^{v} x_i}{v\sigma_x\sigma_s},$$

where $x_{s,i}$ is the set of parameter values leading to stable systems, x_i is the ensemble of parameter values, v is the number of systems in the ensemble, σ_x is the standard deviation of the parameter values, and σ_s is the standard deviation of stability (0 for unstable systems, 1 for stable systems).

Colormaps

To explore the effect of polycentricity or diversity of actors, the exponent parameters are held fixed and assigned the values in Supplementary Table 1 to eliminate variation across exponent parameters as the decision center-resource user connectance and the total size of the system is varied. Connectance represents the proportion of possible interactions in the network that are realized. Since the final system connectance is determined by the strategies actors pursue, it is computed after optimization of actors' strategies rather than fixed a priori.

For each system, the composition is randomly sampled, with a minimum of two resource users, at least one of which is an extractor, and one decision center. In the ternary colormaps (Figure 2.3), the total size of the system is held fixed at 10, and the decision center-resource user connectance is held fixed at 0.4. There are 600 systems sampled for each combination of connectance and size, and 900 for each system composition in the ternary colormaps. Sample sizes were chosen such that additional samples do not significantly change the trends in the colormaps.

2.4 Results and Discussion

2.4.1 Parameter Correlations with Stability

The parameter correlations results reveal that for a smaller system (Figure 2.2a), stabilizing factors include greater capacity gains from external support and gains motivated by resource access conditions, as opposed to gains from collaboration, and greater losses based on attrition rather than being undermined. Conversely, a greater capacity gain from collaboration and capacity loss from undermining by other actors, as well as a greater proportion of actors' efforts spent on collaboration or undermining are destabilizing. This suggests that stronger interactions and greater interdependence among actors is destabilizing, while greater autonomy is stabilizing.

In both the smaller and larger systems (Figure 2.2b), the strategy parameters emerge as important in determining stability. Since the strategies are computed rather than sampled as the other parameters are, the causal effect of the strategies on stability is not clear. However, the results suggest that a greater effort put toward influencing the capacity of decision centers, or venue shopping, corresponds with stability, while greater effort put into the other strategies corresponds with reduced stability. In the example system, agricultural users are engaging in venue shopping by reducing the infrastructure provider's influence over the infrastructure ($K_{1,1}$); if there were other decision centers in the system, they may try to move that authority to a venue that favors agricultural interests. Venue shopping has gained interest as a possible mechanism through which less powerful actors can enact fundamental policy changes (Pralle, 2003). This distinction suggests that venue shopping may arise as a desirable strategy in a different context than other political strategies, or that it changes the system in a fundamentally different manner from other strategies, and that it does so in a lasting manner.

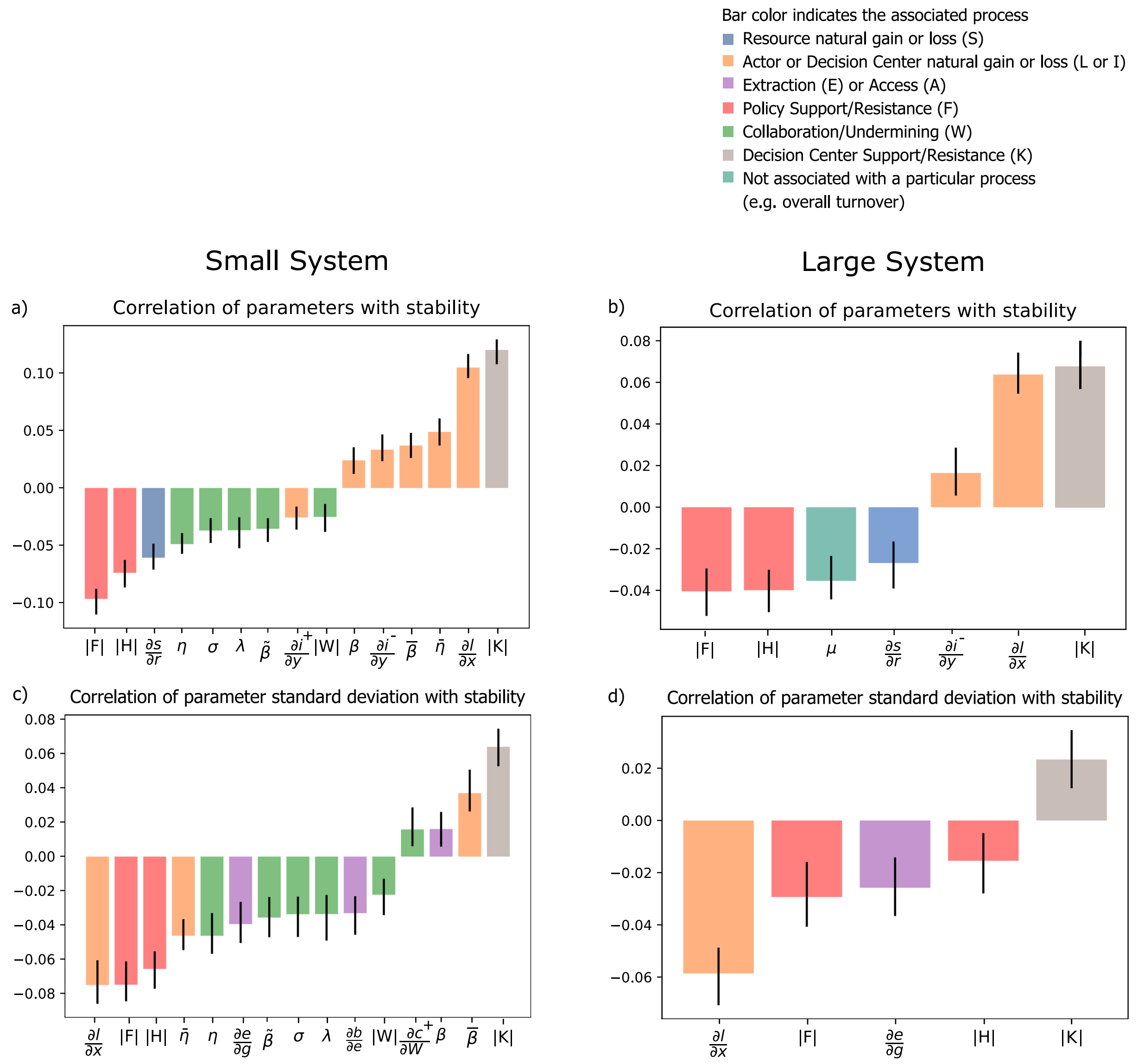

Figure 2.2: Correlation of mean (top) and standard deviation (bottom) of parameters with stability in small (left) and large (right) systems. Only parameters with a statistically significant effect on stability and with a correlation greater than 0.01 are shown. Stabilizing factors include the proportion of effort put into influencing the capacity of decision centers ($|K|$), sensitivity of attrition to the current organizational capacity ($\partial l/\partial x$), the share of loss in capacity due to attrition ($\overline{\eta}$), share of gain in capacity from organization self-growth efforts ($\overline{\beta}$), the sensitivity of decision center loss in capacity to their capacity ($\partial i/\partial y_n$), and the gain in capacity motivated by resource access conditions (β). Destabilizing factors consist of the proportion of effort put into spent on influencing effectiveness of policies ($|F|$ and $|H|$) and on collaborating or undermining ($|W|$), the sensitivity of resource regeneration to the resource state ($\partial s/\partial r$), share of loss in capacity from undermining by other actors (η and λ), share of gain from collaboration ($\widetilde{\beta}$ and σ), and the sensitivity of decision center growth in capacity to their own capacity ($\partial i/\partial y_p$). The standard deviation results reveal that in addition to these parameters, variation in the sensitivity of extraction to the intervention ($\partial e/\partial g$) and the sensitivity of gain in capacity to the ability to extract ($\partial b/\partial e$) is destabilizing.

To understand the effect of heterogeneity among actors' relationships to the resource or to institutions on stability, we look at the variation in the parameters that define, for example, their sensitivity to changes in resource accessibility, or their share of total resource extraction. We find that higher variation in the sensitivity of actors' extraction to governance is destabilizing. This variation corresponds with heterogeneity among resource users in terms of the ease with which their extraction or access can be monitored or regulated. It can also represent institutional diversity, in which decision centers pursue a variety of policies or approaches, which has been hypothesized to increase adaptive capacity (Carlisle and Gruby, 2019). A higher variation in the sensitivity of actors' gain in organizing capacity to their resource access is also destabilizing. Differences in this parameter correspond to different relationships with resource use: actors with low resource requirements, particularly if they are not involved in a profit-driven activity, may experience the largest capacity gains when their ability to extract is low. In contrast, some actors may become more invested and gain greater resources with which to mobilize as their extraction increases. In the example system, for example, urban interests will likely become less engaged once they have sufficient access to water (an inverse relationship between capacity and resource access), whereas agricultural users, particularly industrial agriculture operations, might become less engaged once the available water, and thus profitability of farming, drops below a certain threshold. The presence of both of these relationships to the resource similarly signify heterogeneity and potentially inequity among actors, leading to a greater tendency for contestation and change.

2.4.2 Effect of Polycentrism and Diversity on Stability

The number of different groups in the system, whether actors or decision centers, has a strong effect on stability, while connectance has no noticeable effect on stability (Figure 2.3). This suggests that diversity in actors, a feature of complex and polycentric governance systems, is a destabilizing force. This is consistent with the idea that the inclusion of a greater diversity of actors in governance processes leads to greater flexibility and adaptability, as well as with findings for other complex systems such as ecosystems (May, 1972). The absence of an effect of connectance on stability, however, is in contrast to other complex systems where connectance is destabilizing (May, 1972). This may be because each of the interactions in these systems can influence processes by either increasing or decreasing their effect, unlike in natural systems, where interactions may all push the system in the same direction, leading to greater potential for destabilizing feedbacks. Thus, while greater connectivity in the form of stronger interactions is a destabilizing force, as found in the parameter correlation experiments (Figure 2.2), the presence or absence of interactions is not as important for determining stability in governance systems.

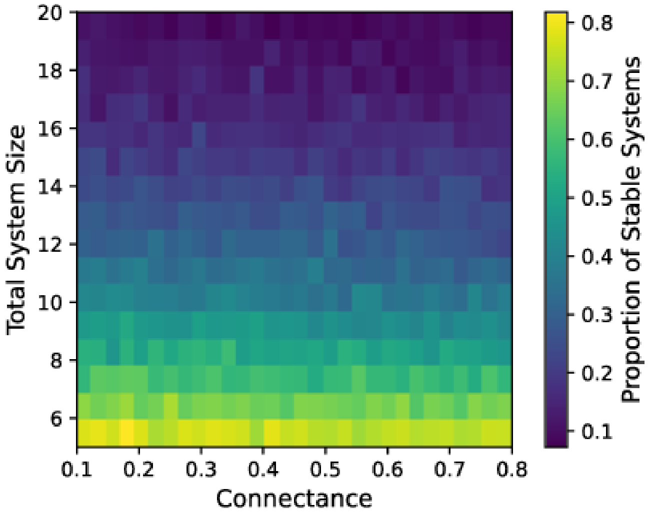

Figure 2.3: Effect of system size (number of actors and decision centers) and connectance on stability. The color represents the proportion of stable systems (out of 600 samples) for each connectance and system size. The connectance shown here is the proportion of links between decision centers and resource users' extraction or access ($G_{1,1}$ and $G_{1,2}$ in Figure 2.1); the same result holds for the total connectance as well (see Figure S2).

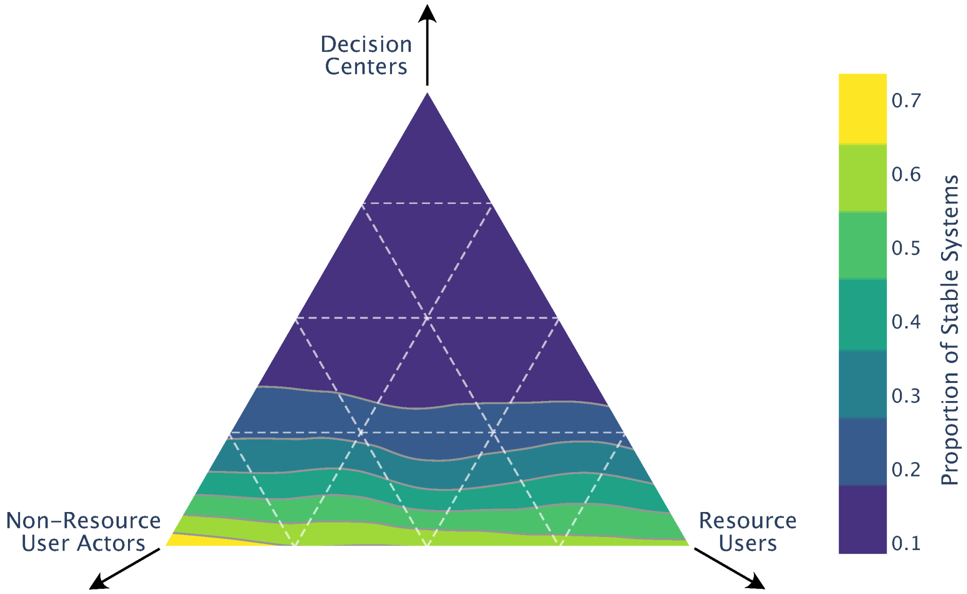

Figure 2.4: Effect of the number of resource users, non-government organizations, and decision centers on stability. The color represents the proportion of stable systems for a given system composition. The total system size is 10, with a minimum of 2 resource users and 1 decision center.

2.4.3 Effect of System Composition on Stability

Finally, looking at the effect of the relative proportions of different entities reveals that stability is determined not just by total diversity, but the diversity in decision centers in particular(Figure 2.3). A greater number of decision centers is destabilizing, while a greater proportion of non-government organizations is stabilizing. The proportion of resource users does not have a strong effect on stability. Whether the resource users are extractive users of the resource also does not have an effect on stability (Figure S3). This result thus supports that polycentrism causes governance systems to be more prone to change, likely because they offer more opportunities for actors to influence the system (Pralle, 2003). Non-government organizations may have a stabilizing effect because of their role in supporting, and thus having aligning goals, with other actors in the system, reducing contestation and helping other actors develop longer-lasting, more durable institutions (Barnes and van Laerhoven, 2015).

2.5 Conclusion

In this study, we propose a modeling framework for resource governance that couples dynamical systems modeling with an agent based model representing actors' strategic interactions with each other and the institutions and organizations mediating their access to a shared resource. By formulating this system as a generalized model,we are able to explore a variety of structures for these relationships, with varying system compositions, types of relationships, connectances, and sizes to identify the factors that influence stability. This approach reveals that greater interdependence and heterogeneity in actors' responses to resource access conditions, as well as in the institutions affecting their resource access, are destabilizing. Additionally, a greater number of different entities, especially a greater number of decision centers, is destabilizing, while greater diversity in non-government organizations is stabilizing. Finally, the strategy of venue shopping corresponds with stability, while strategies such as supporting or undermining other actors or policies correspond with instability.

The applicability of the results are ultimately contingent on whether the modeled processes, such as actor's attempts to navigate governance and support or resist institutions to increase their resource access, are indeed the driving forces in the governance system. Therefore, they may not necessarily apply to governance driven mainly by top-down bureaucratic processes with little stakeholder engagement or with very high capacity to monitor, implement, and enforce policies. Additionally, even though the generalized modeling approach requires fewer assumptions than traditional dynamical systems analysis, there are still assumptions regarding the structure of interactions among different model components. For example, the change in capacity of non-government organizations and decision centers does not directly depend on the resource state, but rather is affected by the resource state only indirectly through its influence on resource users' capacities and actions. Ultimately, we aimed to achieve a balance between a more general model that would make few assumptions about the structure of interactions, but would be challenging to interpret in the context of resource governance systems, and a more structured model, which limits the variety of ways in which variables are linked but provides more precise insight into governance dynamics. Finally, the model assumes a Nash equilibrium in actors' strategies, representing actors as rational and having perfect knowledge of the system and others' actions, rather than the often heuristic and myopic manner in which they actually form their strategies for navigating governance (Pralle, 2003). However, this assumption is more reasonable in stable systems, where repeated interactions in a stable environment allow actors' greater opportunity to learn about the system and fine-tune their strategies (Craig et al., 2017; Pahl-Wostl, 2009).

Despite these limitations, this study provides new insight into the factors that determine how governance systems respond to change, as well as independent support for previously observed benefits of complex governance. Many of the factors commonly associated with complex governance, namely greater interdependence and diversity in actors and decision centers, are destabilizing. This suggests that, similar to other complex systems, complexity in governance systems is destabilizing (May, 1972). It may be this courting of instability that allows for complex governance to be more responsive to external change (Zumsande et al., 2011). However, some results, such as the lack of effect of connectance on stability, contrast with findings for ecosystems, while the stabilizing effect of factors such as a greater number of non-government organizations and venue shopping have not previously been explored systematically. These differences suggest that there is a benefit to modeling the dynamics of governance systems specifically, rather than extending ecological theories to social systems. These results also suggest some concrete strategies to strike a balance between adaptivity and extreme instability in complex governance by, for example, introducing mitigating factors like non-government organizations to help stabilize systems with many different actors.

While modeling is not a replacement for case studies in understanding complex governance, it is complementary by suggesting new theories, such as the stabilizing effect of non-government organizations or of venue shopping, along with providing more detailed insight into existing theories. These results, for example, provide greater insight into the greater adaptivity of polycentric governance by elucidating which factors – such as a greater number and diversity of decision centers as opposed to all entities, and greater interdependence among actors rather than simply the density of connections – lead to greater instability. As suggested by numerous studies (M. D. McGinnis and E. Ostrom, 2012; Stephan, Marshall, and M. McGinnis, 2019; Thiel, Pacheco-Vega, and Baldwin, 2019; Carlisle and Gruby, 2019), this level of detail is necessary in understanding when or why the many benefits ascribed to multi-level, complex, and polycentric systems actually materialize. Additionally, while this study focuses on analyzing theoretical systems, the ability to model the different ways that actors exercise power and the dynamic power relations among them allows for exploring questions relating to the interaction between governance transitions and power relations in empirical systems as well (Avelino and Wittmayer, 2016; Avelino, 2021). This study demonstrates a way forward in combining the insights of complex systems theory with theories on governance to managing complex and highly uncertain human-natural systems in the face of rapid social and environmental change.

2.6 Appendix

Supplementary Methods

Derivation of Generalized Modeling Scale Parameters

We first define the state variables normalized by their steady state value (R^* is the steady state value for R, for example):

$$r := \frac{R}{R^*}, \;\; x_n := \frac{X_n}{X_n^*}, \;\; y_m := \frac{Y_m}{Y_m^*}.$$

Resource Equation

We can then write the normalized functions

$$s(r) := \frac{S(rR^*)}{S^*}$$

and

$$e_n(r, g_{1,n}, \ldots, g_{M,n}) := \frac{E_n(rR^*, G^*_{1,n}g_{1,n}, \ldots, G^*_{M,n}g_{M,n})}{E^*_n},$$

where $g_{m,n}(y_m, F_{1,m,n}x_1, \ldots, F_{K,m,n}x_K) := \dfrac{G_{m,n}(y_mY^*_m, F_{1,m,n}x_1X^*_1, \ldots, F_{K,m,n}x_KX^*_K)}{G^*_{m,n}}$.

This allows us to rewrite the equation for $\dot{R}$ in terms of the normalized variables and functions:

$$\dot{r} = \frac{S^*}{R^*}s - \sum_n \frac{E^*_n}{R^*}e_n.$$

We then define the *scale parameters*

$$\phi := \frac{S^*}{R^*} = \sum_n \frac{E^*_n}{R^*}, \ \ \psi_n := \frac{1}{\phi}\frac{E^*_n}{R^*},$$

and finally rewrite the normalized equation as

$$\dot{r} = \phi\Big(s - \sum_n \psi_n e_n\Big).$$

Resource User and Non-Resource User Actor Equations

We write the normalized functions

$$\begin{aligned} b_n(e_n) := \frac{B_n(E^*_ne_n)}{B^*_n}, \ q_n(a_n) := \frac{Q_n(A^*_na_n)}{Q^*_n}, \\ c^+_{k,n}(W^+_{k,n}x_k) := \frac{C_{k,n}(W^+_{k,n}x_k)}{C^{+*}_{k,n}}, \ c^-_{k,n}(W^-_{k,n}x_k) := \frac{C_{k,n}(W^-_{k,n}x_k)}{C^{-*}_{k,n}}, \\ u_n(x_n) := \frac{U_n(x_nX^*_n)}{U^*_n}, \ l_n(x_n) := \frac{L_n(x_nX^*_n)}{L^*_n}. \end{aligned}$$

where $a_n(r, p_{1,n}, \ldots, p_{M,n})$ and $p_{m,n}(y_m, H_{1,m,n}x_1, \ldots, H_{K,m,n}x_K)$ are defined analogously to e_n and $g_{m,n}$, respectively.

This allows us to rewrite the equation for $\dot{X}_n$ in terms of the normalized variables and functions:

$$\dot{x}_n = \frac{B_n^*}{X_n^*} b_n + \frac{Q_n^*}{X_n^*} q_n + \frac{U_n^*}{X_n^*} u_n + \sum_k \frac{C_{k,n}^{+*}}{X_n^*} c_{k,n}^+ - \sum_k \frac{C_{k,n}^{-*}}{X_n^*} c_{k,n}^- - \frac{L_n^*}{X_n^*} l_n.$$

We then define the *scale parameters*

$$\alpha_n := \frac{B_n^*}{X_n^*} + \frac{Q_n^*}{X_n^*} + \frac{U_n^*}{X_n^*} + \sum_k \frac{C_{k,n}^{+*}}{X_n^*} = \sum_k \frac{C_{k,n}^{-*}}{X_n^*} + \frac{L_n^*}{X_n^*},$$

$$\beta_n := \frac{1}{\alpha_n} \frac{B_n^*}{X_n^*},\ \widehat{\beta}_n := \frac{1}{\alpha_n} \frac{Q_n^*}{X_n^*},\ \overline{\beta}_n := \frac{1}{\alpha_n} \frac{U_n^*}{X_n^*},\ \widetilde{\beta}_n := \frac{1}{\alpha_n} \sum_k \frac{C_{k,n}^{+*}}{X_n^*},\ \sigma_{k,n} := \frac{1}{\alpha_n \widetilde{\beta}_n} \frac{C_{k,n}^{+*}}{X_n^*},$$

$$\overline{\eta}_n := \frac{1}{\alpha_n} \frac{L_n^*}{X_n^*},\ \eta_n := \frac{1}{\alpha_n} \sum_k \frac{C_{k,n}^{-*}}{X_n^*},\ \lambda_{k,n} = \frac{1}{\alpha_n \eta_n} \frac{C_{k,n}^{-*}}{X_n^*}.$$

Finally, we rewrite the normalized equation as

$$\dot{x}_n = \alpha_n \Big(\beta_n b_n + \widehat{\beta}_n q_n + \overline{\beta}_n u_n + \widetilde{\beta}_n \sum_k \sigma_{k,n} c_{k,n}^+ - \eta_n \sum_k \lambda_{k,n} c_{k,n}^- - \overline{\eta}_n l_n \Big).$$

Governance Institution Equations

We write the normalized function

$$i_m^+(y_m, K_{1,m}^+ x_1, \ldots, K_{N,m}^+ x_N) := \frac{I_m^+(y_m Y^*, K_{1,m}^+ x_1 X_1^*, \ldots, K_{N,m}^+ x_N X_N^*)}{I_m^{+*}},$$

and likewise for i_m^-.

This allows us to rewrite the equation for $\dot{Y}_m$ in terms of the normalized variables and functions as

$$\dot{y}_m = \frac{I_m^{+*}}{Y^*} i_m^+ - \frac{I_m^{-*}}{Y^*},$$

which leads us to define the scale parameter

$$\mu_m := \frac{I_m^{+*}}{Y^*} = \frac{I_m^{-*}}{Y^*}.$$

Finally, we rewrite the normalized equation as

$$\dot{y}_m = \mu_m \left(i_m^+ - i_m^- \right).$$

Jacobian and Exponent Parameters

We find the relevant *exponent parameters* by looking at the corresponding entries of the Jacobian.

From the Resource Equation

$$\frac{\partial \dot{r}}{\partial r} = \phi \left(\frac{\partial s}{\partial r} - \sum_n \psi_n \frac{\partial e_n}{\partial r} \right)$$

$$\frac{\partial \dot{r}}{\partial x_i} = -\phi \sum_n \psi_n \sum_m \frac{\partial e_n}{\partial g_{m,n}} \cdot \frac{\partial g_{m,n}}{\partial (F_{i,m,n} x_i)} \cdot F_{i,m,n}$$

$$\frac{\partial \dot{r}}{\partial y_m} = -\phi \sum_n \psi_n \frac{\partial e_n}{\partial g_{m,n}} \cdot \frac{\partial g_{m,n}}{\partial y_m}$$

From the Resource User and Non-Resource User Actor Equations

$$\frac{\partial \dot{x}_n}{\partial r} = \alpha_n \left(\beta_n \frac{\partial b_n}{\partial e_n} \cdot \frac{\partial e_n}{\partial r} + \widehat{\beta}_n \frac{\partial q_n}{\partial a_n} \cdot \frac{\partial a_n}{\partial r} \right)$$

For $i \neq n$:

$$\begin{aligned}
\frac{\partial \dot{x}_n}{\partial x_i} = \alpha_n \Bigg(& \beta_n \frac{\partial b_n}{\partial e_n} \cdot \sum_m \frac{\partial e_n}{\partial g_{m,n}} \cdot \frac{\partial g_{m,n}}{\partial (F_{i,m,n} x_i)} \cdot F_{i,m,n} \\
& + \widehat{\beta}_n \frac{\partial q_n}{\partial a_n} \cdot \sum_m \frac{\partial a_n}{\partial p_{m,n}} \cdot \frac{\partial p_{m,n}}{\partial (H_{i,m,n} x_i)} \cdot H_{i,m,n} \\
& + \widetilde{\beta}_n \sigma_{i,n} \frac{\partial c_{i,n}^+}{\partial (W_{i,n}^+ x_i)} W_{i,n}^+ - \eta_n \lambda_{i,n} \frac{\partial c_{i,n}^-}{\partial (W_{i,n}^- x_i)} W_{i,n}^- \Bigg)
\end{aligned}$$

For $i = n$:

$$\begin{aligned}\frac{\partial \dot{x}_n}{\partial x_n} = \alpha_n \Bigg(& \beta_n \frac{\partial b_n}{\partial e_n} \cdot \sum_m \frac{\partial e_n}{\partial g_{m,n}} \cdot \frac{\partial g_{m,n}}{\partial (F_{n,m,n} x_n)} \cdot F_{n,m,n} \\ & + \widehat{\beta}_n \frac{\partial q_n}{\partial a_n} \cdot \sum_m \frac{\partial a_n}{\partial p_{m,n}} \cdot \frac{\partial p_{m,n}}{\partial (H_{n,m,n} x_n)} \cdot H_{n,m,n} \\ & + \overline{\beta}_n \frac{\partial u_n}{\partial x_n} - \overline{\eta}_n \frac{\partial l_n}{\partial x_n} \Bigg)\end{aligned}$$

$$\frac{\partial \dot{x}_n}{\partial y_m} = \alpha_n \left(\beta_n \frac{\partial b_n}{\partial e_n} \cdot \frac{\partial e_n}{\partial g_{m,n}} \cdot \frac{\partial g_{m,n}}{\partial y_m} + \widehat{\beta}_n \frac{\partial q_n}{\partial a_n} \cdot \frac{\partial a_n}{\partial p_{m,n}} \cdot \frac{\partial p_{m,n}}{\partial y_m} \right)$$

From the Governance Institution Equations

$$\frac{\partial \dot{y}_m}{\partial r} = 0$$

$$\frac{\partial \dot{y}_m}{\partial x_i} = \mu_m \left[\frac{\partial i_m^+}{\partial (K_{i,m}^+ x_i)} K_{i,m}^+ - \frac{\partial i_m^-}{\partial (K_{i,m}^- x_i)} K_{i,m}^- \right]$$

$$\frac{\partial \dot{y}_m}{\partial y_m} = \mu_m \left[\frac{\partial i_m^+}{\partial y_m} - \frac{\partial i_m^-}{\partial y_m} \right]$$

For $j' \neq m$:

$$\frac{\partial \dot{y}_m}{\partial y_{j'}} = 0$$

Derivation of Objective Function Gradient

At equilibrium, the equation

$$\frac{d}{d\mathfrak{p}} \begin{pmatrix} r^* \\ x_n^* \\ y_m^* \end{pmatrix} = -J^{-1} \begin{pmatrix} \frac{\partial \dot{r}}{\partial \mathfrak{p}} \\ \frac{\partial \dot{x}_n}{\partial \mathfrak{p}} \\ \frac{\partial \dot{y}_m}{\partial \mathfrak{p}} \end{pmatrix}$$

describes how the steady state changes with respect to a strategy parameter $\mathfrak{p}$. The following sections show the calculation of the right-hand side of this equation for each of the strategy parameters.

Calculation of Right-Hand Side

Calculations for $F_{k,m,n}$

$$\frac{\partial \dot{r}}{\partial F_{k,m,n}} = -\phi\psi_n \frac{\partial e_n}{\partial g_{m,n}} \cdot \frac{\partial g_{m,n}}{\partial (F_{k,m,n} x_k)}$$

$$\frac{\partial \dot{x}_i}{\partial F_{k,m,n}} = \begin{cases} \alpha_n \beta_n \dfrac{\partial b_n}{\partial e_n} \cdot \dfrac{\partial e_n}{\partial g_{m,n}} \cdot \dfrac{\partial g_{m,n}}{\partial (F_{k,m,n} x_k)} & \text{if } i = n \\ 0 & \text{if } i \neq n \end{cases}$$

$$\frac{\partial \dot{y}_j}{\partial F_{k,m,n}} = 0$$

Calculations for $H_{k,m,n}$

$$\frac{\partial \dot{r}}{\partial H_{k,m,n}} = 0$$

$$\frac{\partial \dot{x}_i}{\partial H_{k,m,n}} = \begin{cases} \alpha_n \widehat{\beta}_n \dfrac{\partial q_n}{\partial a_n} \cdot \dfrac{\partial a_n}{\partial p_{m,n}} \cdot \dfrac{\partial p_{m,n}}{\partial (H_{k,m,n} x_k)} & \textbf{if } i = n \\ 0 & \textbf{if } i \neq n \end{cases}$$

$$\frac{\partial \dot{y}_j}{\partial H_{k,m,n}} = 0$$

Calculations for $W^+_{k,n}$ and $W^-_{k,n}$

$$\frac{\partial \dot{r}}{\partial W^+_{k,n}} = 0$$

$$\frac{\partial \dot{x}_i}{\partial W^+_{k,n}} = \begin{cases} \alpha_n \widetilde{\beta}_n \sigma_{k,n} \dfrac{\partial c^+_{k,n}}{\partial (W^+_{k,n} x_k)} & \text{if } i = n \\ 0 & \text{if } i \neq n \end{cases}$$

$$\frac{\partial \dot{y}_j}{\partial W^+_{k,n}} = 0$$

$$\frac{\partial \dot{r}}{\partial W^-_{k,n}} = 0$$

$$\frac{\partial \dot{x}_i}{\partial W^-_{k,n}} = \begin{cases} -\alpha_n \eta_n \lambda_{k,n} \dfrac{\partial c^-_{k,n}}{\partial (W^-_{k,n} x_k)} & \text{if } i = n \\ 0 & \text{if } i \neq n \end{cases}$$

$$\frac{\partial \dot{y}_j}{\partial W^-_{k,n}} = 0$$

Calculations for $K^+_{k,m}$ and $K^-_{k,m}$

$$\frac{\partial \dot{r}}{\partial K^+_{k,m}} = 0$$

$$\frac{\partial \dot{x}_i}{\partial K^+_{k,m}} = 0$$

$$\frac{\partial \dot{y}_j}{\partial K^+_{k,m}} = \begin{cases} \mu_m \dfrac{\partial i^+_m}{\partial (K^+_{k,m} x_k)} & \text{if } j = m \\ 0 & \text{if } j \neq m \end{cases}$$

$$\frac{\partial \dot{r}}{\partial K^-_{k,m}} = 0$$

$$\frac{\partial \dot{x}_i}{\partial K^-_{k,m}} = 0$$

$$\frac{\partial \dot{y}_j}{\partial K^-_{k,m}} = \begin{cases} -\mu_m \dfrac{\partial i^-_m}{\partial (K^-_{k,m} x_k)} & \text{if } j = m \\ 0 & \text{if } j \neq m \end{cases}$$

Calculating how objective functions change with each parameter

Extraction

We have

$$\frac{de_n}{dF_{l,j,n}} = \frac{\partial e_n}{\partial r}\frac{\partial r^*}{\partial F_{l,j,n}} + \sum_m \left(\frac{\partial e_n}{\partial g_{m,n}} \frac{\partial g_{m,n}}{\partial y_m} \frac{\partial y^*_m}{\partial F_{l,j,n}} + \sum_k \frac{\partial e_n}{\partial g_{m,n}} \frac{\partial g_{m,n}}{\partial (F_{k,m,n} x_k)} \frac{\partial x^*_k}{\partial F_{l,j,n}} \cdot F_{k,m,n} \right) + \frac{\partial e_n}{\partial g_{j,n}} \frac{\partial g_{j,n}}{\partial (F_{l,j,n} x_l)}.$$

For any other effort allocation parameter $\mathfrak{p}$, including $\mathfrak{p} = F_{l,j,i}$ when $i \neq n$, we can use the general formula

$$\frac{de_n}{d\mathfrak{p}} = \frac{\partial e_n}{\partial r}\frac{\partial r^*}{\partial \mathfrak{p}} + \sum_m \left(\frac{\partial e_n}{\partial g_{m,n}} \frac{\partial g_{m,n}}{\partial y_m} \frac{\partial y^*_m}{\partial \mathfrak{p}} + \sum_k \frac{\partial e_n}{\partial g_{m,n}} \frac{\partial g_{m,n}}{\partial (F_{k,m,n} x_k)} \frac{\partial x^*_k}{\partial \mathfrak{p}} \cdot F_{k,m,n} \right).$$

Access

We have

$$\frac{da_n}{dH_{l,j,n}} = \frac{\partial a_n}{\partial r}\frac{\partial r^*}{\partial H_{l,j,n}} + \sum_m \left(\frac{\partial a_n}{\partial p_{m,n}} \frac{\partial p_{m,n}}{\partial y_m} \frac{\partial y^*_m}{\partial H_{l,j,n}} + \sum_k \frac{\partial a_n}{\partial p_{m,n}} \frac{\partial p_{m,n}}{\partial (H_{k,m,n} x_k)} \frac{\partial x^*_k}{\partial H_{l,j,n}} \cdot H_{k,m,n} \right) + \frac{\partial a_n}{\partial p_{j,n}} \frac{\partial p_{j,n}}{\partial (H_{l,j,n} x_l)}.$$

For any other effort allocation parameter $\mathfrak{p}$, we can use the general formula

$$\frac{da_n}{d\mathfrak{p}} = \frac{\partial a_n}{\partial r}\frac{\partial r^*}{\partial \mathfrak{p}} + \sum_m \left(\frac{\partial a_n}{\partial p_{m,n}} \frac{\partial p_{m,n}}{\partial y_m}\frac{\partial y_m^*}{\partial \mathfrak{p}} + \sum_k \frac{\partial a_n}{\partial p_{m,n}}\frac{\partial p_{m,n}}{\partial (H_{k,m,n}x_k)}\frac{\partial x_k^*}{\partial \mathfrak{p}} \cdot H_{k,m,n} \right).$$

Parameter Values and Ranges

Parameters are derived from the Generalized Modeling approach described above.

Parameter	**Interpretation**	**Range**	**Value**
Scale Parameters			
ϕ	Rate of turnover in the resource, or inverse of characteristic time scale of resource	0 to 1	
ψ_n	Share of extraction of resource by user n	0 to 1, $\sum_n \psi_n = 1$	
α_n	Rate of turnover in the capacity of user n	0 to 1	
β_n	Share of actor n capacity gain in response to resource extraction	$\beta_n + \widehat{\beta}_n + \widetilde{\beta}_n + \overline{\beta}_n = 1$	
$\widehat{\beta}_n$	Share of actor n capacity gain in response to resource access conditions	$\beta_n + \widehat{\beta}_n + \widetilde{\beta}_n + \overline{\beta}_n = 1$	
$\widetilde{\beta}_n$	Share of actor n capacity gain from collaborations	$\beta_n + \widehat{\beta}_n + \widetilde{\beta}_n + \overline{\beta}_n = 1$	
$\overline{\beta}_n$	Share of actor n's capacity gain from "natural" gain (non-resource users only)	$\beta_n + \widehat{\beta}_n + \widetilde{\beta}_n + \overline{\beta}_n = 1$	
$\sigma_{k,n}$	Share of actor n's collaboration gain from collaborating with actor k	0 to 1	
η_n	Share of actor n's loss in capacity due to direct undermining by other actors	$1 - \overline{\eta}_n$	

$\lambda_{k,n}$	Share of actor n's loss from being undermined by other actors attributed to actor k	0 to 1	
$\overline{\eta}_n$	Share of actor n's loss in capacity due to "natural" decay	$1 - \eta_n$	
μ_m	Rate of turnover in decision center m's capacity	0 to 1	
Exponent Parameters			
$\frac{\partial s}{\partial r}$	Sensitivity of resource regeneration to resource state	-1 to 1	-0.5
$\frac{\partial e_n}{\partial r}$	Sensitivity of extraction by user n to resource state	1 to 2	1.5
$\frac{\partial e_n}{\partial g_{m,n}}$	Sensitivity of extraction by user n to intervention by decision center m (effectiveness of intervention)	-1 to 1	-
$\frac{\partial g_{m,n}}{\partial (F_{i,m,n} x_i)}$	Sensitivity of intervention in user n's extraction by decision center m to actions by actor i (effectiveness of actors' support/resistance)	0 to 2	1
$\frac{\partial g_{m,n}}{\partial y_m}$	Sensitivity of extraction intervention by decision center m to their own capacity	0 to 2	1
$\frac{\partial p_{m,n}}{\partial y_m}$	Sensitivity of resource access intervention by decision center m to their own capacity	0 to 2	1
$\frac{\partial b_n}{\partial e_n}$	Sensitivity of user n's gain in capacity based on extraction to the amount of extraction	-1 to 1	0.5
$\frac{\partial a_n}{\partial r}$	Sensitivity of access by user n to resource state	0 to 2	1

$\frac{\partial q_n}{\partial a_n}$	Sensitivity of user n's gain in capacity based on resource access to the level of resource access	-1 to 1	0.5
$\frac{\partial a_n}{\partial p_{m,n}}$	Effectiveness of intervention p by decision center m in changing access for resource user n	-1 to 1	-
$\frac{\partial p_{m,n}}{\partial (H_{i,m,n} x_i)}$	Sensitivity of intervention by decision center m to actions by actor i (effectiveness of actors' support/resistance)	0 to 2	1
$\frac{\partial c^+_{i,n}}{\partial (W^+_{i,n} x_i)}$	Sensitivity of actor n's gain from collaboration to actor i's collaboration efforts	0 to 2	1
$\frac{\partial c^-_{i,n}}{\partial (W^-_{i,n} x_i)}$	Sensitivity of actor n's loss in capacity to other actor i's efforts to undermine them	0 to 2	1
$\frac{\partial l_n}{\partial x_n}$	Sensitivity of actor n's "natural" decay in capacity l to their own capacity	0.5 to 1	1
$\frac{\partial u_n}{\partial x_n}$	Sensitivity of non-resource user actor n's self-growth in capacity to their own capacity	0 to 1	0.5
$\frac{\partial i^+_m}{\partial (K^+_{i,m} x_i)}$	Sensitivity of decision center m's gain in capacity to actor i's actions; likewise for $\frac{\partial i^-_m}{\partial (K^-_{i,m} x_i)}$	0 to 2	1
$\frac{\partial i^+_m}{\partial y_m}$	Sensitivity of decision center m's gain in capacity to their own capacity	0 to 1	0.5
$\frac{\partial i^-_m}{\partial y_m}$	Sensitivity of decision center m's loss in capacity to their own capacity	0 to 1	1

Supplementary Figures

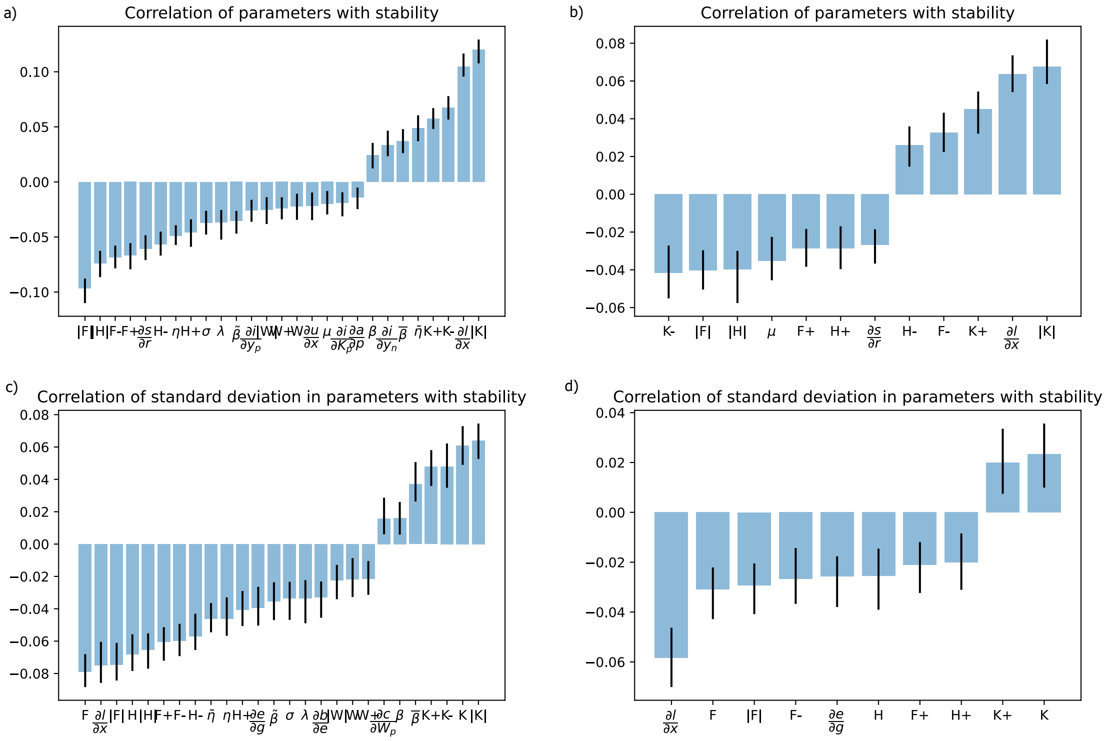

Figure S1: Correlation results including all forms of strategy parameters and all significant parameters. The inclusion of the different forms of strategy parameters allows for concluding that stability depends on the magnitude of effort allocated to the strategies rather than the sign or direction of the effort.

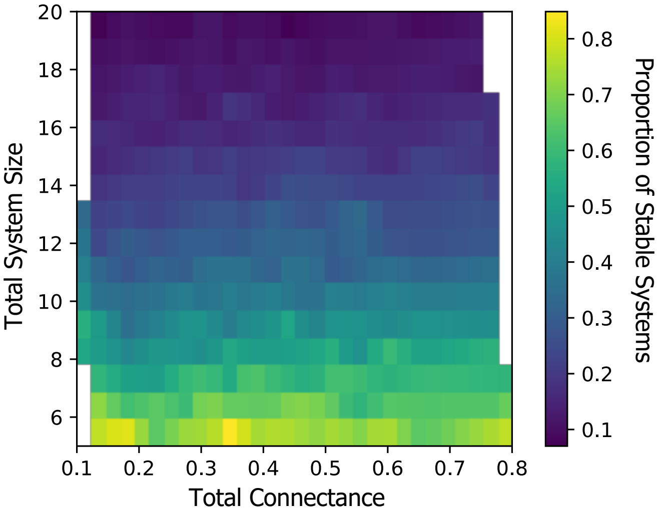

Figure S2: Effect of system size (number of actors and decision centers) and connectance on stability. The connectance shown is the total connectance, which is computed after the experiment rather than set beforehand due to the dependence of the connectance on actors' computed strategies. As a result, there is no data for some combinations of connectance and size.

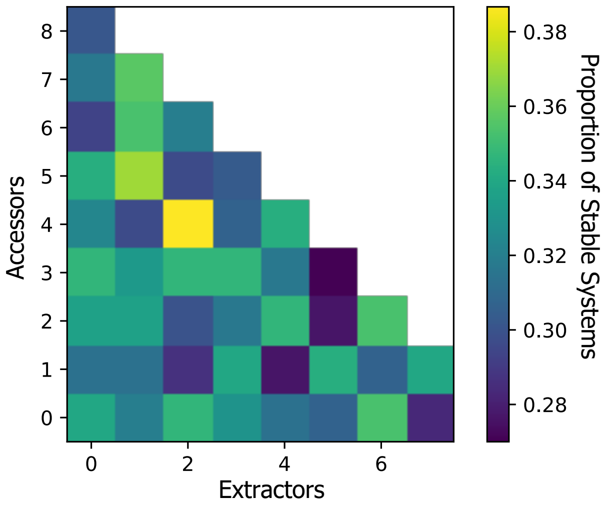

Figure S3: Effect of different types of resource users (extractors, accessors, and combined extractors and accessors) on stability. The color represents the proportion of stable systems for a given system composition. The total system size is 10, with 8 resource users and 2 decision centers. The proportion of extractors as compared to accessors or combined extractors and accessors has no effect on stability.

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Chapter 3

Contested Flows: A narratives and systems modeling approach to understanding water governance transformations

3.1 Abstract

Broad transformations in natural resources governance are increasingly understood through a complex adaptive systems perspective, as well as recognized as processes that are deeply political and fraught with power in how different visions and goals of transformation are considered, and in who benefits from them. Exploring both of these aspects of transformations simultaneously to understand how different actors pursue and envision change in feedback with the structures that shape their ability to pursue these visions is challenged by the methodological divide between modeling and power-focused approaches. This study bridges this gap by combining analysis of diverse and conflicting understandings of and visions for water and governance, with dynamical systems modeling of the complex feedbacks among actors, natural resources, and institutions, to explore the emergent interactions between actors' narratives, knowledge, and strategies, and how these shape different actors' power over and vulnerability to changes. This approach is developed in the context of water governance in California's San Joaquin Valley, a heavily agricultural region with disparities in water access and political power in the midst of transition. Through interviews and focus groups with growers, various advocacy groups, and residents of rural communities, distinct narratives emerge around the role of local versus higher-level governance in addressing water issues, and the role of different types of knowledge in governance. Additionally, modeling the strategies that maximize each water users' access to water reveals a conflict between environmental justice narratives and optimal strategies that primarily benefit larger growers. For rural communities, this manifests in a strategy that is oriented towards long-term transformation rather than short-term gain, and for small growers, is reflected in a diversity of narratives that vary in their alignment with larger growers. Finally, modeling the implications of the different visions for governance for actors' influence and sensitivity to change reveals greatly differentiated impacts on different water users and reinforces the likelihood of governance changes mainly benefiting the most powerful without more fundamental changes to both social and biophysical relationships.

3.2 Introduction

There is a growing recognition of the need for fundamental changes in the economic, political, and physical structures that mediate our relationships with our most critical resources. Central to these transformations is governance, in which different and conflicting visions of change are negotiated through relationships of conflict and collaboration among state and non-state actors (Patterson et al., 2017; Smith, Stirling, and Berkhout, 2005; Loorbach, 2010; Krueger et al., 2022). The study of these processes draws on complex adaptive systems concepts including self-organization, feedbacks, and multiple potential equilibria. This focus brings together the actor-focused and the structural to understand how bottom-up processes of change, arising from interactions among networks of actors engaged in innovation, collaboration, resistance, and negotiation, influence and are influenced by broader structures (Loorbach, 2010).

At the same time, transformation studies emphasize that there is not a single, objective system and the contested nature of which types of knowledge are considered, which system understandings are valid, which goals are pursued, and the pathways taken to get there. They document how entrenched institutions aim to retain power by closing down the possibilities and understandings of issues, and social movements contest these framings, and the often technocratic solutions focused on stability and control that they imply, by opening up the framing of issues to diverse and lived experiences, particularly of the most marginalized (Patterson et al., 2017; Leach, Scoones, and Stirling, 2010; Andy Stirling, 2015; Stirling, 2011). Power is thus central to if and how transformations occur, and different forms of power interact in shaping different actors' abilities to shape it – instrumental/material power deriving from access to monetary, human, and natural resources, structural power based in governance structures and institutions, and discursive power based in the ability to create discourses that shape which issues are on the agenda and how they are discussed (Avelino, 2021; Patterson et al., 2017; Geels, 2014).

The qualitative study of sustainability transformations understands these concepts of complexity, subjectivity, and power to be linked. The complex and uncertain nature of social-ecological systems and governance raises the need to consider diverse perspectives and different types of knowledge, and it is through complex feedbacks that structures of power often reinforce themselves (Leach, Scoones, and Stirling, 2010). Modeling approaches to understanding system transformations have yet to fully integrate power and diverse perspectives, however. Models have proven powerful tools in revealing and analyzing different system attractors and how system-level dynamics emerge from interactions among actors, institutions, infrastructure and resources (Mirza et al., 2019; J. Anderies, Janssen, and

Schlager, 2016; Muneepeerakul and J. M. Anderies, 2020; Muneepeerakul and J. M. Anderies, 2017; Lade, Niiranen, et al., 2015; Lade, Tavoni, et al., 2013). They thus have unrealized potential in exploring alternative configurations of these interactions and how material and structural power shape how actors can exert agency in influencing transformation processes. This study aims to realize this potential through a dynamical systems modeling approach that captures complex interactions while retaining enough tractability to explore many different potential systems, while also recognizing the need to complement modeling with qualitative approaches to better understand discursive power, heterogeneity among actors, and the subjective and socially constructed nature of system dynamics. Thus, this study is centered on narratives, which offer understandings of how a given problem has arisen, why it matters, and how to solve it. Narratives have long been studied as a powerful tool in shaping collective attitudes and behavior regarding environmental issues and governance, perceptions of the possibilities for change (Agrawal, 2005; Burchell, Gordon, and Miller, 1991; Partelow et al., 2020), and in motivating and driving the social movements that realize these possibilities (M. Ingram, H. Ingram, and Lejano, 2019). This study aims to understand through both qualitative analysis and modeling why, and among whom, different narratives of governance arise, how these narratives interact with actors' strategies and goals for change in governance, and what the visions of governance implied by different narratives mean for different actors' power over and vulnerability to changes. The contribution of this study, therefore, is in developing an approach that realizes the potential of combining systems models with qualitative approaches to explore emergent phenomena arising from complex interactions while also centering power-laden relationships and conflicting discourses and visions for change in environmental governance.

3.2.1 Case Study Background

This interaction between narratives, knowledge, strategies, and power is examined in the context of water governance in California's San Joaquin Valley, a region characterized by increasing aridity in the face of climate change (Swain et al., 2018; Rhoades, Jones, and Ullrich, 2018), decades of overextraction of groundwater (Hanak et al., 2019), complex and heavily contested institutions and infrastructure (Pannu, 2012a), and high levels of poverty and inequity in water access (Martin and Taylor, 1998; London et al., 2018). The development of the state, and the San Joaquin Valley especially, has been shaped by the one of the most elaborate water systems in the world, which was created in large part to allow for the intensive and industrialized agriculture that now dominates the Valley (Preston, 1981; McWilliams, 1939). The allocation of surface water through this system is heavily contested among agricultural, environmental, and urban interests and negotiated through a combination of individually held water rights and contracts with the state and federal reservoir projects. Additionally, groundwater overdraft disproportionately impacts the low-income rural and unincorporated communities in the basin that rely on relatively shallower wells that risk going dry as groundwater tables drop, as well as suffer from nitrate contamination from fertilizer and naturally occurring arsenic contamination (Pauloo et al., 2020; Community Water Center et al., 2014; Harter et al., 2012).

The communities most impacted by water access issues consist of the farm workers, largely immigrants (U.S. Department of Agriculture and National Agricultural Statistics Service, 2012), whose low-wage labor has enabled large-scale farming (McWilliams, 1939). Yet, these communities remain lacking in investment and critical infrastructure, with much of the benefits from agriculture taken out of region (Goldschmidt, 1947). Historic and racialized marginalization and under-investment are exacerbated by governance structures that disadvantage these communities. Many disadvantaged communities are unincorporated, which means they lie outside of city limits and therefore interface with only the county, rather than two layers of local governance, the city and the county, as residents of cities do. This leads to a lack of representation and investment, with the responsibility of providing drainage, sewer, and water services for unincorporated communities passed onto more competitive state and federal funding sources (London et al., 2018). Many residents of these communities also lack citizenship, and therefore formal representation in their county and district, and face a language barrier in communicating with those who are supposed to represent them (Community Water Center et al., 2014). In addition, the complexity and fragmentation of responsibility presents a barrier for residents of rural communities seeking accountability (Pannu, 2012a). Part of the fragmentation of water governance includes the proliferation of water districts, which perpetuate the exclusion of disadvantaged communities. In particular, quasi-public irrigation districts, which are more common in the valley than public districts, limit voting rights to those who own land (Pannu, 2012a). Many weight the power of votes by the size of a landowner's property (Pannu, 2012a), ensuring the largest landowners have greater political power in local water management decisions. Small and minority growers are similarly disadvantaged by these structures which limit their representation in irrigation districts or exclude them altogether if they lease their land, as is disproportionately the case for minority growers.

As the San Joaquin Valley undergoes the process of implementing the Sustainable Groundwater Management Act (SGMA), the first statewide groundwater governance mandate, these issues determine who is able to participate in and benefit from the governance processes that are evolving. Research on SGMA so far suggests that its devolution to the local level has led to the solidification of the power of existing local agencies such as water districts, which have largely taken on the role of Groundwater Sustainability Agencies (GSAs) that are responsible for creating plans for complying with SGMA, perpetuating the exclusion of rural communities (Dobbin, 2020). Similarly, smaller growers and growers in white areas, or areas outside of irrigation district boundaries, lack formal representation and the political capital to participate in GSAs, despite also being among the most impacted by the overexploitation of groundwater (Mendez-Barrientos et al., 2020).

The San Joaquin Valley, therefore, exemplifies a system in the midst of dire environmental changes as well as potentially transformative governance changes. Analysis of these potential changes consists of three main parts: 1) A qualitative analysis of discourses about knowledge in governance, and the role of governance in creating and solving water issues, 2) Modeling the strategies that maximize actors' water access to understand how system structure shapes and constrains options for actors, and how narratives interact with actors' goals and strategies, and 3) Modeling the implications of different visions for governance, drawn from the narrative analysis, for different actors' power and vulnerability in the system.

3.3 Methods

3.3.1 Data Collection

The study uses 23 semi-structured interviews as well as 2 focus groups with a total of 44 participants (Table 3.1). Interviews and focus groups were conducted throughout 2020-2022. Focus groups were conducted in person, while interviews were conducted virtually. Interviews lasted approximately an hour on average, and focus groups lasted three hours. One focus group and one interview was conducted in Spanish with the assistance of a translator, for a total of thirteen Spanish speakers, while the remaining focus groups and interviews were conducted in English. Participants were selected based on being located in the Southern San Joaquin Valley or working with an organization that works closely with residents or growers in the region. They were also selected based on their connections to water advocacy and outreach groups or local governance, and thus are not likely to be representative of growers or residents as a whole. Rather, since the goal is to understand experiences and narratives of navigating governance, participants are more likely to have experience in navigating water governance. Participating rural residents are from various rural unincorporated communities throughout the Tulare Basin, and growers are diverse in terms of crops grown and race, with farm sizes ranging from 60 to 1600 acres. It is worth noting that there is little direct representation of very large farm owners or managers for investor-owned farms in the sample, though many of the agricultural organizations represented work closely with or have leadership consisting largely of larger growers. Additionally, indigenous residents of

Sector/Background	Number of Participants
Grower	4
DAC resident	24
Agricultural Outreach/Advocacy organization	7
Environmental Justice nonprofit	3
Irrigation/Water District	4
Resource Conservation District	1
Academic Researcher	1
Total	**44**

Table 3.1: Characteristics of study interviewees. Note that many interviewees hold multiple roles (e.g. a community resident that is also on a local water board) but for the purposes of this table, are only counted once.

the Valley are underrepresented, with one tribal member and one organization that works with tribes in the sample. Finally, due to the shift from focus groups to interviews during the pandemic, only rural community residents were included in focus groups. In order to mimic some of the effects of focus groups, interviewees were prompted with responses from other interviews. However, the use of focus groups with community residents may have led to greater consensus and more comprehensive knowledge represented in their responses.

Interviews and focus groups consisted of two main parts. The first was focused around understanding how they identify themselves or the group their organization works with (e.g. small or large growers, rural community residents), their perception of the water-related issues affecting this group, and how this group is affected or responding to this issue, along with any intra-group differences determining its impacts. The second part of the interview centered around a mapping exercise that draws heavily on Net-Map, an exercise that has been used to monitor policy interventions, coordinate multi-stakeholder governance, and facilitate community-based projects (Schiffer, 2007). This exercise focuses on 1) who the influential actors in terms of the water issue they identified, 2) the role of these actors and how they interact with each other, and 3) the changes, whether structural or qualitative, that would improve outcomes for the group in question. This map was visible to participants throughout the interviews to ensure that it matched their understanding of the system.

3.3.2 Data Analysis

The focus groups and interviews is analyzed through two rounds of qualitative coding. The first round of coding occurred concurrently with data collection to allow for iterative exploration of the concepts that emerged in the interviews and focus groups. This process focuses on understanding participants' experiences of governance, intra-group heterogeneity and conflicts, and the reasons underlying actors' strategies or goals. Contextual information about participants such as farm size, ethnic background, use of groundwater or surface water, or drinking water system type is also noted.

The second round of coding is used in conjunction with the network representations from the mapping exercise to parameterize different realizations of a model of governance that uses a Generalized Modeling approach. The network conceptualizations from interviews and focus groups are aggregated and then, combined with the second round of coding, translated into parameter ranges from which different system realizations are sampled.

Governance Modeling Approach

Generalized modeling is an approach to dynamical systems analysis that allows for directly constructing the Jacobian based on a conceptualization of the system structure and interactions without specific functional forms, and involving parameters with intuitive interpretations (Gross and Feudel, 2006). Generalized Modeling has been used to model empirical social-ecological dynamics (Lade and Niiranen, 2017), to explore regime shifts in social-ecological systems (Lade, Tavoni, et al., 2013), and model the stability of environmental governance (Molla et al., 2022). This study, however, is the first to combine generalized modeling with qualitative analysis. This modeling approach is uniquely suited to being combined with qualitative data and analysis by requiring the minimum information needed to describe long-term system behavior, limiting the assumptions necessary and allowing for describing system properties in terms of the relative importance and sensitivity of different processes, which is much easier to elicit in interviews than the information necessary for specifying functional forms. Additionally, the ease of exploring different systems by changing these properties, as opposed to analyzing different sets of equations as in traditional dynamical systems modeling, lends itself to exploring conflicting visions of these processes.

The modeling approach used in this study is a specific manifestation of the generic modeling approach developed in Molla et al. 2022, with some modifications to reflect additional types of interactions that arose during interviews, as well as incorporating multiple sources of water available in the system. Similar to the original model, the modeling approach consists of state variables representing 1) bio-physical variables indicating the quantity of surface water and groundwater, and groundwater quality; the organizational capacity of 2) resource user organizations or interest groups, which directly impact or are impacted by the resource state, and can represent both extractive and non-extractive users; 3) non-government organizations, or private institutions, which are not directly impacted by the resource state but still have interests in the system (e.g. nonprofits, advocacy and education groups), and 3) decision centers and public institutions, which have the ability to directly mediate resource users' interactions with the resource. Organizational capacity broadly refers to resources such as volunteer or staff labor, access to legal, technical, or administrative expertise, funds, or grassroots engagement that allow actors to pursue their political goals. Each of these variables is described in more detail below. A full description of the model can be found in the Supplementary Methods.

Water Resources Variables

The model consists of three state variables related to water resources in the Tulare Lake Basin: 1) The aggregate quantity of surface water held in reservoirs that contribute to flow into the Delta and in the major local reservoirs of Pine Flat and Isabella. Even though only a portion of Delta outflows are delivered to the San Joaquin Valley, this proportion is mediated by water rights and infrastructure constraints, both of which are determined by the political processes represented in the model. Therefore, the total amount of water stored in reservoirs is treated as potentially available to the Valley. 2) The quantity of groundwater in the Tulare Lake Basin aquifer, and 3) The quality of groundwater in the Tulare Lake Basin aquifer. The quality of the groundwater is modeled because of its importance as the main source of drinking water for rural communities in the basin.

Surface water is modeled by Equation 3.1, where S_1 represents net inflow, $E_{1,n}$ the rate of loss from extraction by water user n, T the total rate of recharge from surface water to groundwater, and L_1 the natural loss or outflow. T is thus represented as a loss for surface water and a gain for groundwater. Since extraction and recharge are both mediated by policies and infrastructure, $E_{1,n}$ and T are both in turn functions of interventions by private and public institutions, which can increase or decrease water users' ability to access surface water. These interventions themselves are functions of the product of actors' organizational capacities and the proportion of their effort that they allocate to influencing that intervention (e.g. through lobbying, refusal to comply with regulations, or advocacy). Therefore, through these multiple levels of nested functions, water availability, the strength of institutions that mediate water users' access to water, and the efforts of resource users' to influence the capacity of these institutions are intertwined.

$$\dot{R}_1 = S_1(R_1) - \sum_n E_{1,n} - T - L_1(R_1) \tag{3.1}$$

Groundwater availability is modeled similarly by Equation 3.2, with the only difference being that the recharge from surface water to groundwater, T, is represented as a gain rather than a loss.

$$\dot{R}_2 = S_2(R_2) + T - \sum_n E_{2,n} - L_2(R_2) \tag{3.2}$$

Finally, groundwater quality is represented by Equation 3.3. R_3 represents abstractly the aggregate contaminant concentration of the groundwater, rather than any specific contaminant. This state variable therefore works differently from surface and groundwater availability in that a lower level is desirable. Consistent with representing a concentration, R_3 depends on groundwater quantity such that increases in the groundwater level from natural and managed aquifer recharge, S_2 and T, respectively, decrease the contamination level, and a greater quantity of groundwater mitigates contamination to an extent by diluting contaminants over a greater volume. D_n represents the rate of discharge of contaminants by water user n and similarly to extraction and recharge, is a function of interventions by private and public institutions, which are then subject to interventions by actors.

$$\dot{R}_3 = \frac{1}{R_2}\left[\sum_n D_n - R_3\left[S_2(R_2) + T\right]\right] \tag{3.3}$$

Actor and Decision Center Organizational Capacity Variables

The organizational capacity of water users, non-government organizations, and decision centers is modeled by Equation 3.4, where U_t represents their gain and loss in capacity based on their own capacity, representing for example, growth due to recruitment or word of mouth, and loss due to attrition and switching attention to other issues, respectively. $\sum B_{r,n}$ represents user n's gain in capacity motivated by their access to water, aggregated across groundwater, surface water, groundwater quality, representing either actors becoming more agitated due to lack of access, or more invested in ensuring continued water access as their water use, and thus the value associated with it, increases. $\sum_a C_{a,t}$ represents the aggregate gain from collaboration with or support from other actors or loss from being undermined or demobilized by other actors, and $\sum_m P_{m,t}$ represents the aggregate gain or loss in capacity from governmental policies. P is differentiated from C by being subject to other actors' efforts to influence the policies that increase or decrease actors' capacities, representing how P is a result of public policies that are subject to public scrutiny and intervention.

$$\begin{aligned}\dot{X}_t =& U_t^+(X_t) + \sum_r B_{r,n}(E_{r,n}) + \sum_a C_{a,t}^+ + \sum_m P_{m,t}^+ \\ & - \sum_a C_{a,t}^- - \sum_m P_{m,t}^- - U_t^-(X_t)\end{aligned} \tag{3.4}$$

The model is parameterized such that entities whose capacity is not directly influenced by water access, namely non-government organizations and decision centers, do not have a gain based on the resource ($\sum B_{r,n}$ in Equation 3.4).

Translating Qualitative Information into Model Parameters

The generalized modeling procedure involves normalizing Equations 3.1-3.4 with respect to the steady state and computing the Jacobian (for the full description of the steps, see Molla et al. (2022) and Gross and Feudel (2006)). This process produces two types of parameters: scale parameters and exponent parameters. Scale parameters denote the magnitude of fluxes, such as turnover rates or the relative importance of different processes, while exponent parameters indicate the sensitivity of a process to another process or variable. In general, scale parameter ranges were derived from statements of the form, “X is more important than Y/is the most important in determining Z”, as well as through counting mentions of each process during coding to determine the relative importance of different processes. For example, in determining the relative importance of different organizations and programs as sources of support for small growers, we counted mentions of different organizations by small growers and organizations working with small growers. The proportion of mentions of any particular organization was then used as the average proportion of support that organization contributed when sampling that scale parameter. The exponent parameters are parameterized based on statements about the sensitivity of one process to another. For example, there are multiple exponent parameters in the model indicating how much of an effect actors have on policy, which are parameterized based on actors’ assessments of how responsive different government entities have been to their efforts, or how much of an influence they have been able to have on policy. Where there are disagreements, parameters are sampled to include the range of values suggested by actors. Where there is not enough information for a parameter, a default range of values that encompasses the plausible range of parameters is sampled. See Supplementary Methods for the full model parameterization.

Optimizing Political Strategies

Actors' political strategies consist of how they allocate their organizational capacity among different actions: 1) Intervening in institutions that mediate water access (intervening in $E_{r,n}$ in Equations 3.1-3.4), 2) supporting or undermining the capacity of another actor (affecting $C_{a,t}$ in Equation 3.4), 3) supporting or undermining governmental support of another actor (affecting $P_{m,t}$ in Equation 3.4). In order to explore how knowledge, access to resources, and narratives influence water users' political strategies, we compare actual and optimized strategies for each of the water users represented in the sample. Their actual strategies are parameterized based on inteview and focus group responses, as described previously. The optimal strategy is the one that maximizes a particular water users' equilibrium access to water, represented by the sum of their E_r across the different water sources, weighted by the importance of that water source, given all other actors' actions. The optimal strategies are found for an ensemble of 300 system parameterizations.

Computing Influences and Sensitivities Under Different Scenarios

To explore the implications of different water management and governance scenarios, as derived from the narratives emerging from interviews and focus groups, we calculate influence and sensitivity metrics for each water user in each scenario (Aufderheide et al., 2013). The influence and sensitivity of each water user is determined based on the eigenvalues and eigenvectors of the Jacobian. For each eigenvalue of the Jacobian, there is a corresponding right eigenvector and left eigenvector. The right eigenvectors govern how the system returns to the steady state after a perturbation, while the left eigenvectors indicate the strength of the response when a given state variable–in this case, the capacity of an actor–is perturbed. Thus, the left eigenvectors indicate the influence of a particular water user while the right eigenvectors indicate their sensitivity to perturbations. See Supplementary Methods for the details of the influence and sensitivity calculations.

3.4 Results

3.4.1 The role of knowledge in governing and navigating governance

Unanimous among interviewees was the sentiment that water and water governance in the San Joaquin Valley is extremely complex from a biophysical, legal, and political standpoint. Thus it is no surprise that the need for knowledge, whether to comply with, influence, or create policies was a frequent theme in interviews. Three types of knowledge emerged as important for navigating governance and governing: system knowledge, local/lived knowledge, and scientific knowledge. However, different groups conceptualized the way that these types of knowledge interacted with governance and the types of knowledge needed to govern differently.

The fragmented and institutionally complex nature of the system meant that system knowledge frequently came up as a necessity for those seeking to influence water governance. For residents of rural communities and small growers, the need for knowledge of "how the system works" is a gatekeeping mechanism that makes it difficult for them to hold entities accountable. Those with the knowledge or resources to understand complex regulations are seen as being able to strongly influence or even circumvent the law. One small farmer explains how those with access to lawyers "*always have many different ways to see it and read it and that's when the attorneys are a key player here because they can find a way of going around*" (Interview 5, small grower). Community organizations such as environmental justice nonprofits or farmer advocacy groups play an important role in this respect by helping disadvantaged groups overcome institutional complexity to understand to whom to apply pressure in order to solve their issues.

The role of lived experience and local knowledge in governance surfaced in interviews with all groups. For example, community residents, speaking about a member of the Tulare County Board of Supervisors they had recently elected, explain, *"now we actually have a person that has walked our shoes and has lived in our community and had relatives in these communities with water issues and that in itself makes a big difference*" (Focus Group 1, community resident). For rural communities, this perspective empowers them to pursue grassroots organizing to elect local officials with lived experience of drinking water issues, as well as ensure their voice is heard at the state level. The larger growers in the sample also expressed the importance of local knowledge in decisionmaking, and express frustration with how policymakers do not seem to respect this knowledge. A farmer complains, "*none of the higher-ups listen to anything like boots on the ground experience like you know, my dad's got 50 years of experience out here, he knows what's going on*" (Interview 21, grower). In contrast to community residents, though, growers use the concept of local knowledge to advocate for local control of water regulations, with the idea that conditions are very locally specific and that therefore policies need to tailored to local contexts. Small and minority growers, despite the very specific and often culturally rooted knowledge involved in cultivating diverse crops, in contrast, do not claim this type of knowledge. A representative from an organization that works with minority growers explains that this may be because, "*their educational level might not be as high as third grade so meeting with these higher ups in Sacramento or local politicians they're very...intimidated, you know just they don't feel like they should be at that level, even though they more than belong at that seat in that table talking with that politician*" (Interview 4, agricultural outreach organization). How different actors conceive of the legitimacy of their own knowledge and involvement in governance plays an important role in explaining differences in involvement.

Finally, the role of scientific knowledge came up frequently, particularly among larger growers. Growers questioned whether water policies were truly based on science, and argued that the state selectively uses scientific studies to justify passing mandates. For example, with regards to nitrogen management policy, a grower argued that the state "*had one researcher go out basically and do a literature review and from that concluded that all nitrogen that is not taken up by the plant basically goes to the water. . . . and that was never questioned by anybody on that state board or staff because it was what they wanted to hear*" (Interview 15, grower). Growers also questioned the accuracy of information disseminated by the state and by environmental justice organizations, claiming that this information tended to be one-sided. By disputing the scientific basis of water policy, growers claim objective scientific knowledge in a way that other groups do not.

3.4.2 Alternative Narratives of Water and Governance

While growers and rural community residents had diverse experiences and issues with governance, four main narratives of the issues emerged. These narratives are distinguished by how they identify the main water-related issue in the region, explain how this problem came about, and conceptualize a solution and the role of government in the creating or perpetuating the problem or potential solution. These were not mutually exclusive or incompatible with each other, and multiple of them often coexisted within a single interview.

Framing of Main Water Issue	Solution	Groups Using Narrative
Regulatory Drought	Less regulation, greater local autonomy, development of more water infrastructure	Large growers
Physical Availability and Quality of Water	More efficient irrigation, recharge, improved nutrient management practices	Small and large growers, agricultural research/outreach groups
Lack of Oversight and Regulation	Stricter regulation, increased funding to provide clean water	Small growers, rural communities, environmental justice groups
Exploitative Nature of Agriculture	Develop alternatives to industrial agriculture, change relationship between agriculture and rural communities	Small growers, rural communities, environmental justice groups

Previous research found a collective aversion to state control among growers (Mendez-Barrientos et al., 2020), a finding that held true to an extent in this study as well. Multiple growers and representatives of agricultural organizations identified lack of water access as primarily a regulatory issue rather than a biophysical one. Where they acknowledge issues of over-extraction, subsidence, and groundwater contamination, they consider them isolated incidents caused by a few bad actors rather than systemic issues, and thus that most growers did not require state intervention in order to ensure groundwater sustainability. Additionally, they point to how regulatory hurdles prevent them from accessing increased surface water to help address these issues, such as through environmental flow requirements or preventing the construction of new reservoirs. Growers also feel villianized by the environmental discourse, which they feel focuses only on the amount of water they use, and not the contributions to food supply, livelihoods of rural communities in the region, or habitat that they are able to make due to that water use. Interestingly, even growers who had their own water access impacted by a larger neighboring grower expressed alignment with these larger growers on some issues. This may be a result of the collective identity formed by the sense of having been villianized as a group, making them feel kinship even with those neighbors that have had negative impacts on their water access, or a recognition of the benefits of working with their larger and more powerful counterparts. However, in contrast to previous findings, this framing was far from unanimous among growers. Many growers and organizations, especially those representing the smallest growers or minority growers, felt that groundwater had been unregulated for too long (lack of oversight narrative).

A second narrative focused on the physical availability of water, or the physical aspects of water contamination was common among staff of collaborative agriculture-focused organizations as well as some growers. This framing focused on technical solutions to water issues, though with some recommendations for governance changes that would facilitate those solutions. Water issues were best solved collaboratively with growers, industry experts, and researchers working together to find and implement practices that would reduce water use and contamination. This framing does not place environmental issues and drinking water in conflict with agriculture and suggests that win-win solutions are possible. It also promotes collaboration among agencies, as well as between the local and state levels. There is ultimately a strong emphasis on local autonomy, though the role of the state in coordination and providing resources is acknowledged. This perspective embraces the proposed benefits of polycentric governance in the literature, with a less centralized structure allowing for more experimentation, while coordination and collaboration allows for sharing and supporting ideas that work.

The third narrative is focused on groundwater over-exploitation and contamination as a regulatory problem. In this narrative, groundwater should have been regulated earlier by the state in order to protect domestic drinking water as well as smaller growers, both of whom cannot afford deeper wells. This issue is addressed by stricter regulation of polluters and growers, particularly those powerful enough to exploit loopholes. This narrative was common among environmental justice organizations and some small growers and grower organizations. While these small growers and organizations acknowledged the regulatory burden they face, they suggest exceptions in these regulations to prevent dispoportionate burden on small growers rather than doing away with these regulations altogether, in contrast to the regulatory burden narrative, This framing favors greater intervention at the state level to ensure equity at the local level, because "*local control just means local power brokers jockeying over decisions*" (Interview 3, Environmental Justice nonprofit).

Finally, the exploitative nature of agriculture framing emerges from the belief that though rural communities are economically dependent on agriculture, that the relationship between agriculture and communities has been exploitative, as has the relationship between agriculture and the environment. A community resident explains that for her fellow residents who are farmworkers, industrial agriculture "*just contributes to them, you know having to stay in a situation where they don't have a clean drinking water, they don't have infrastructure, and I mean when you think about also just the work it just keeps them so busy, and so tired*" (Interview 16). This framing also recognizes that changing climactic and water governance conditions may pose an existential threat to farming in the San Joaquin Valley in its current form, and advocates for changes to agriculture that not only increase its resilience, but also allows rural communities to reap more of its benefits. This perspective arose among some small grower advocacy groups and community residents.

3.4.3 System Conceptualizations and Strategies

System conceptualizations from the mapping exercises were aggregated to create Figures S1 and S2. Water quality and water supply are diagrammed separately for ease of interpretation, but are modeled together. The diagrams reveal a highly complex governance system composed of several interconnected issues: drinking water access, groundwater quality regulation, surface water provision, and managed aquifer recharge. For the most part, interviewees did not conflict with each other about the interactions or processes in the system, but rather presented different subsets of the system based on the issues they were most concerned about or familiar with. The next several sections examine the interaction between water users' system conceptualizations, narratives, and strategies by comparing their actual and "optimal" strategies. The optimal strategies are not a representation of how actors should behave, but rather of the opportunities and constraints generated by the current governance system, and deviations from these strategies elucidate actors' objectives and abilities to navigate these opportunities.

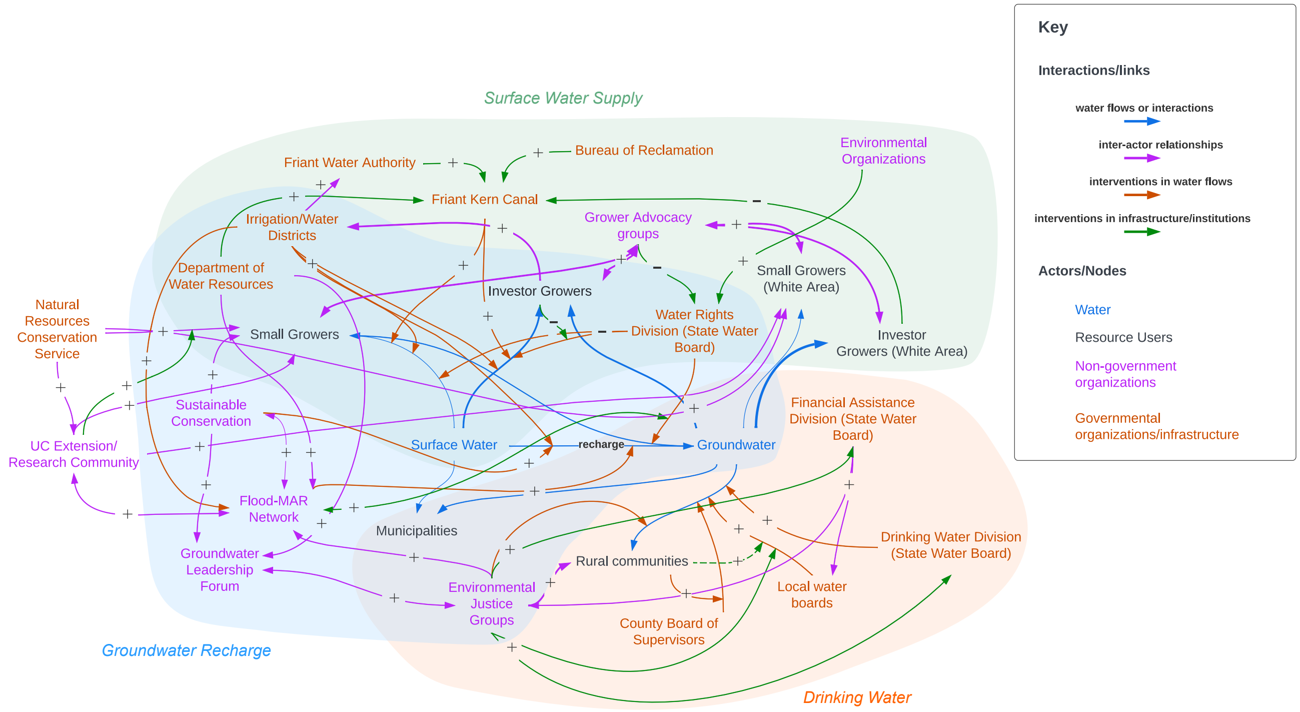

Figure S1: Aggregated System Conceptualization of Water Supply Governance

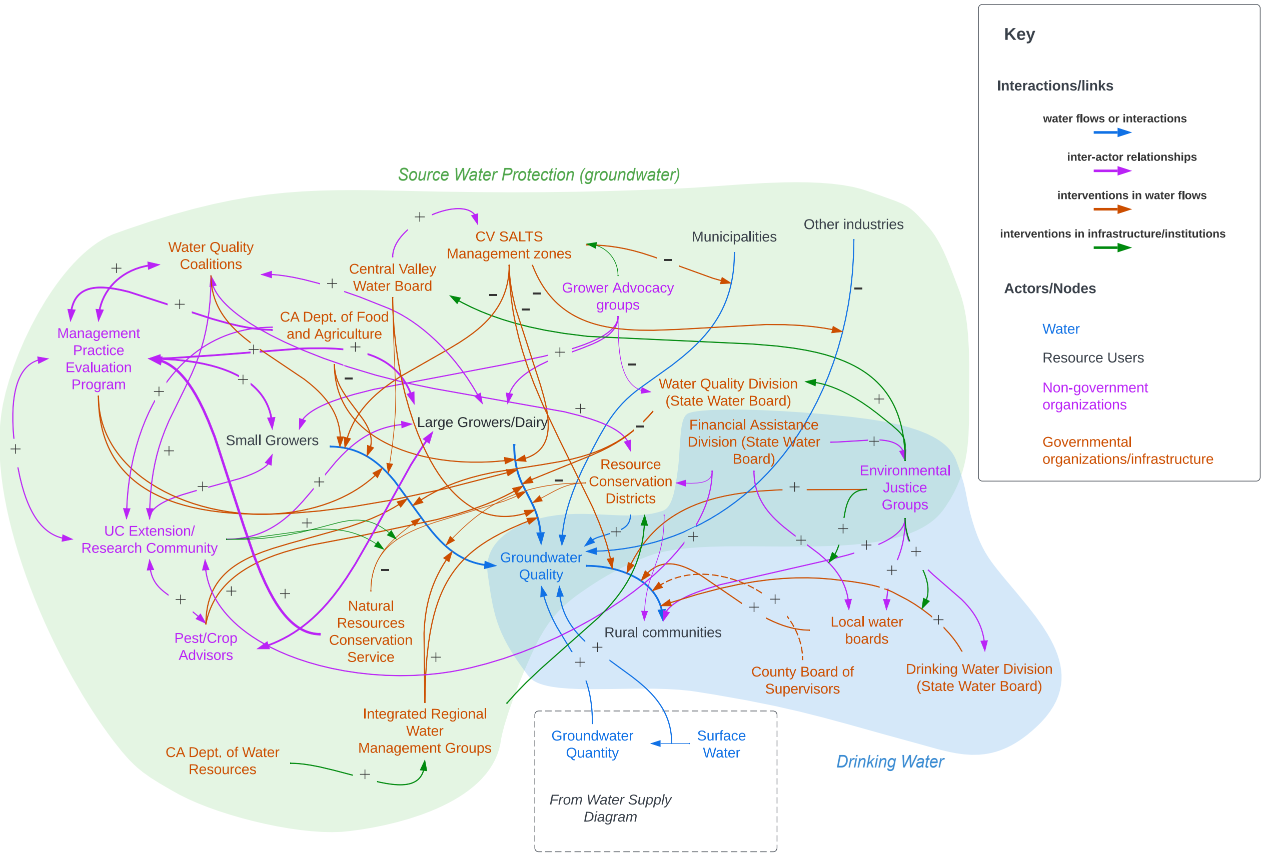

Figure S2: Aggregated System Conceptualization of Water Quality Governance

Rural Communities

Residents of rural communities have the most complicated optimal strategy, likely because the issue of access to drinking water intersects with water quality and water supply issues. Source water protection in particular accounts for much of the unfulfilled optimal strategy. Rural residents rarely identified these entities or policies as drivers in access to clean drinking water, suggesting that this gap is attributable to a lack of understanding of the highly fragmented system of groundwater quality regulation and management, which involves numerous interacting government agencies, organizations, and policies (Pannu, 2012b). Environmental justice organizations, however, did identify these entities and are involved in supporting water quality regulation efforts.

Community residents did identify entities that they directly interacted with, such as the community organizations or funding programs that directly provide outreach or support, or local governance entities that influence their daily life. Community residents, for example, are very knowledgeable and well connected to numerous environmental justice organizations, and could identify local entities and those directly related to drinking water in their communities such as local water boards, County Board of Supervisors, and the role of the State Water Resources Control Board in regulating community drinking water systems. Residents of rural communities identified environmental justice groups as important and powerful players, whereas staff of these groups contend that residents overestimate their influence and underestimate the importance of their local water boards, often failing to hold them accountable as a result.

The optimization also suggests supporting larger growers' access to surface water by opposing state restrictions on grower access to surface water, supporting irrigation districts that distribute surface water to growers, and supporting investments in the infrastructure that conveys surface water to growers. This strategy increases water access by rural communities, who rely solely on groundwater, because increased surface water availability displaces grower extraction of groundwater, at least in the short term, as well as increasing the availability of water for groundwater recharge. However, this strategy is not one that is pursued by rural community residents or by environmental justice organizations, likely because it conflicts with their narratives for who is responsible for drinking water issues – namely, weak regulations and an exploitative agricultural industry – and thus should be responsible for addressing these issues. This suggests that their actions are driven by a desire for more fundamental reform rather than increasing their water access within the status quo. That the strategies involved in pursuing these goals is so different suggests an incompatibility between environmental justice and maximizing any single actor's access to water without more fundamental changes to the system.

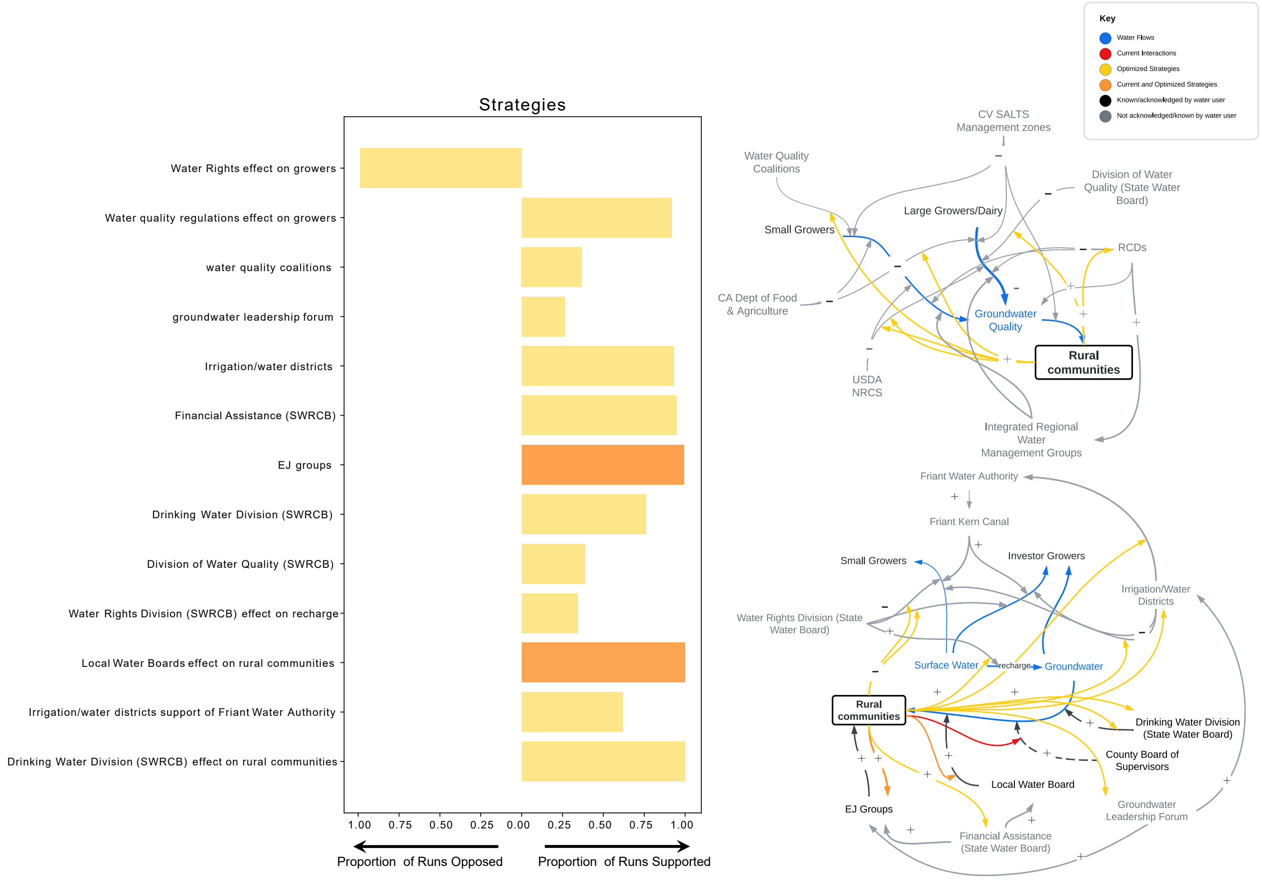

Figure S3: Current and optimized strategies for rural community residents

Small and White Area Growers

The interviews suggest that small growers, especially minority growers, are largely not very involved in water governance due to a lack of capacity and distrust of governmental entities. They usually identified local governance entities such as Irrigation Districts or Water Quality Coalitions, and were very knowledgeable about sources of funding and support from programs such as the State Water Efficiency & Enhancement Program through the Natural Resources Conservation Service, and organizations such as UC Cooperative Extension or the Farm Bureau that provide outreach and technical support.

Similar to rural communities, the strategy optimization (FigureS4) reveals a seemingly non-intuitive strategy for small growers and white area growers of supporting larger growers access to surface water by opposing restrictions on their surface water access and supporting the efforts of irrigation districts to secure water for growers. While it may seem that small growers' competition with larger growers for access to surface and groundwater puts them in conflict with larger growers, the optimization suggests that large growers are powerful enough in influencing policies to ensure more surface water is allocated to growers in general, including smaller growers and growers currently without access to surface water, that their water access overall benefits from supporting large growers. While interviewees representing larger growers expressed this belief in win-win solutions that benefit the Valley as a whole as part of the regulatory burden and physical availability narratives, the views of small growers were more complicated and sometimes conflicting. This result may help explain why despite the acknowledgement by small growers of their greater sensitivity to availability of groundwater and surface water compared to larger growers, who had deeper pumps and could afford to pay higher rates to obtain alternative sources of water, they also sometimes expressed a sense of shared interest with larger growers in the face of new regulations. The optimization result suggests that this seeming contradiction is not only about a shared identity formed around anti-regulation or anti-government discourses, but potentially the result of recognizing who holds power and the constraints on the possibilities for increased water access within the current system.

Large and Investor Growers

The larger growers interviewed tended to be very knowledgeable about water quality regulations and water supply issues, and engaged in multiple venues for local water governance, including their irrigation or water districts and water quality coalitions. As noted by small growers and agricultural outreach organizations, this participation is driven by the ability of large, and especially investor growers, to hire staff to manage administrative tasks and consultants to stay informed about and adapt to new and often complex regulations. Unsurprisingly, larger growers actual strategies closely align with their optimized strategies (Figure S5), suggesting that larger growers are largely able to pursue strategies that maximize their access to water. The only exception is that the optimal strategy suggests that growers should support irrigation and water districts in investing in restoring or increasing the capacity of the Friant Kern Canal, which delivers surface water to growers. This may be attributed to the indirectness of this strategy in benefitting growers' access to water, as well as the collective action problem created by multiple entities being responsible for funding maintenance and repairs for the canal. Overall, though, the optimization results suggest that larger growers are indeed driven by the objective of maximizing their water access, consistent with their narratives about water governance, and tend to have access to the knowledge and resources that allow them to pursue that objective.

3.4.4 Actors' Influences and Sensitivities Under Different Scenarios

As demonstrated by the strategy optimization, different water users face different abilities to influence water governance, especially in ways that both maximize their access to water and advances other goals such as sustainability and equity. In this section, we further explore how the structure of governance shapes how actors can influence, and are influenced by, water

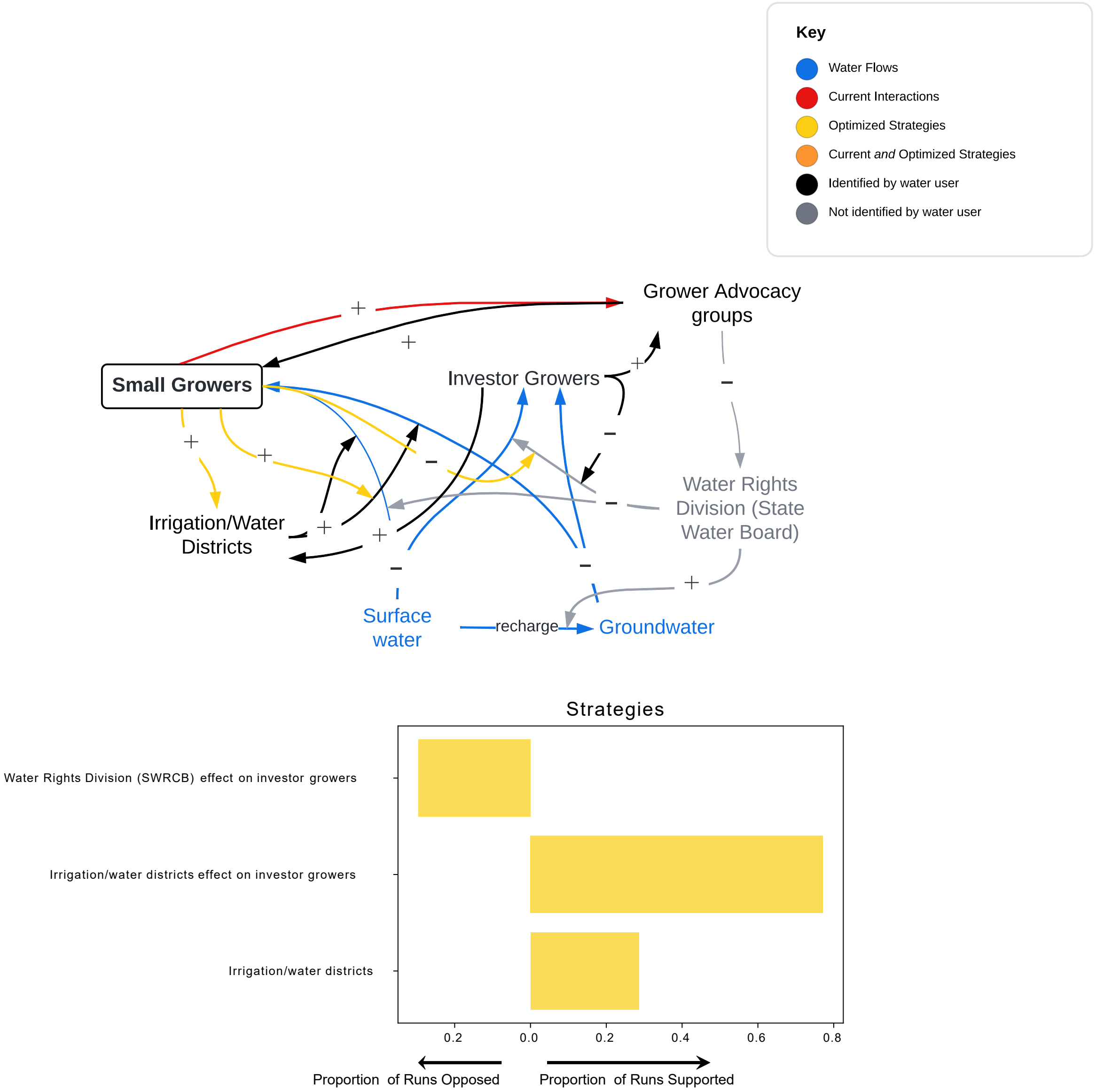

Figure S4: Current and Optimized Strategies for Small Growers

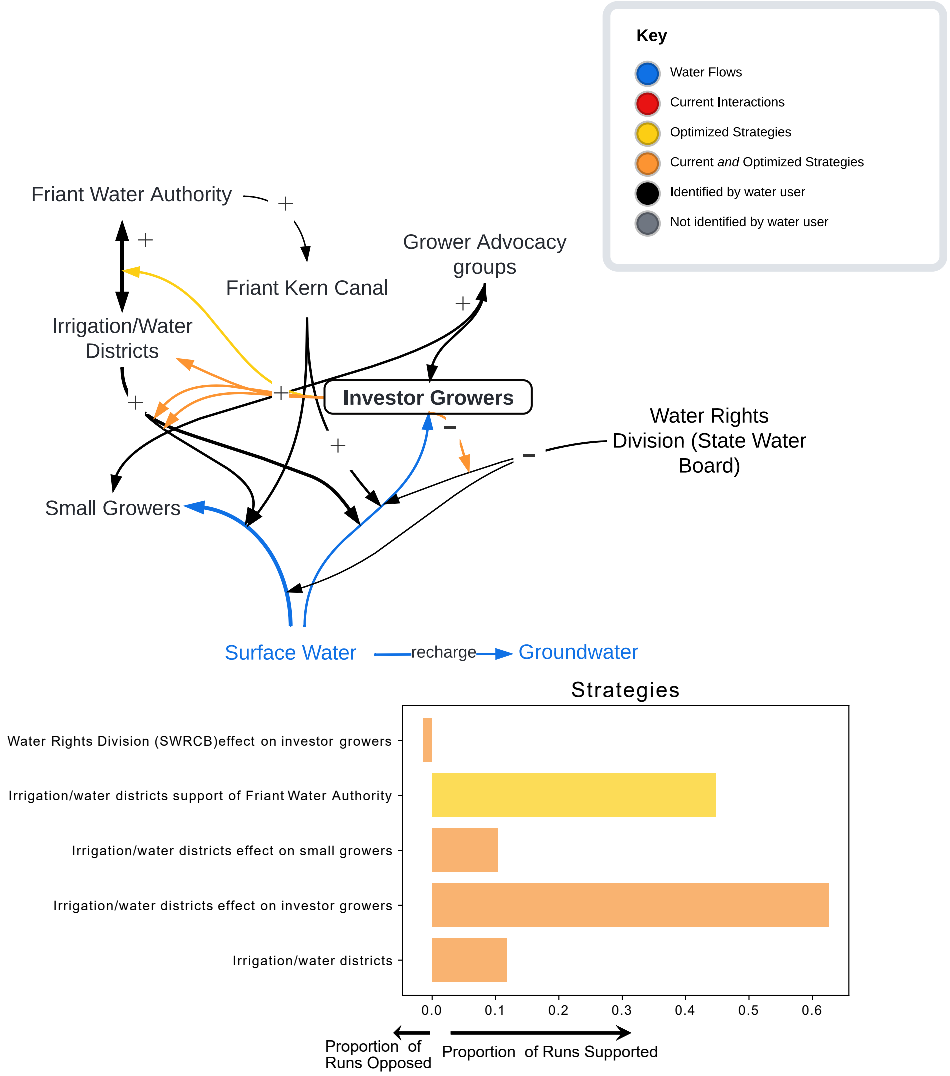

Figure S5: Current and Optimized Strategies for Large Growers governance by modeling an idealized version of the system based on each of the narratives. These idealized visions are:

1. **Ending the "regulatory drought":** parameterized to reflect increased availability and extraction of surface water supplies in the Valley, such as from increasing deliveries from the Delta and building additional reservoirs. It also represents the provision of surface water to growers currently in white areas, increased influence of irrigation and water districts over surface water provision and water quality regulations being eliminated.

2. **Improved water management and coordination:** parameterized to reflect groundwater management that is largely controlled by irrigation and water districts, as under SGMA, as well as increased managed aquifer recharge, and increased support and collaboration between agricultural non-government organizations and government entities, and between state-level government entities.

3. **Increased state oversight:** parameterized to represent groundwater management controlled by the state, stronger groundwater quality protections, reduced groundwater extraction and increased managed aquifer recharge, increased governmental support for environmental justice and sustainable agriculture organizations, and increased engagement of rural communities in groundwater management.

4. **Changing the nature of agriculture:** parameterized to reflect reduced number and size of larger or investor growers, stronger groundwater quality protections, reduced total groundwater and surface water extraction and a shift in water use from agriculture to non-agriculture-based industries, increased managed aquifer recharge, increased governmental support for environmental justice and sustainable agriculture organizations, increased engagement of rural communities in groundwater management, and mutual support between small growers and rural communities.

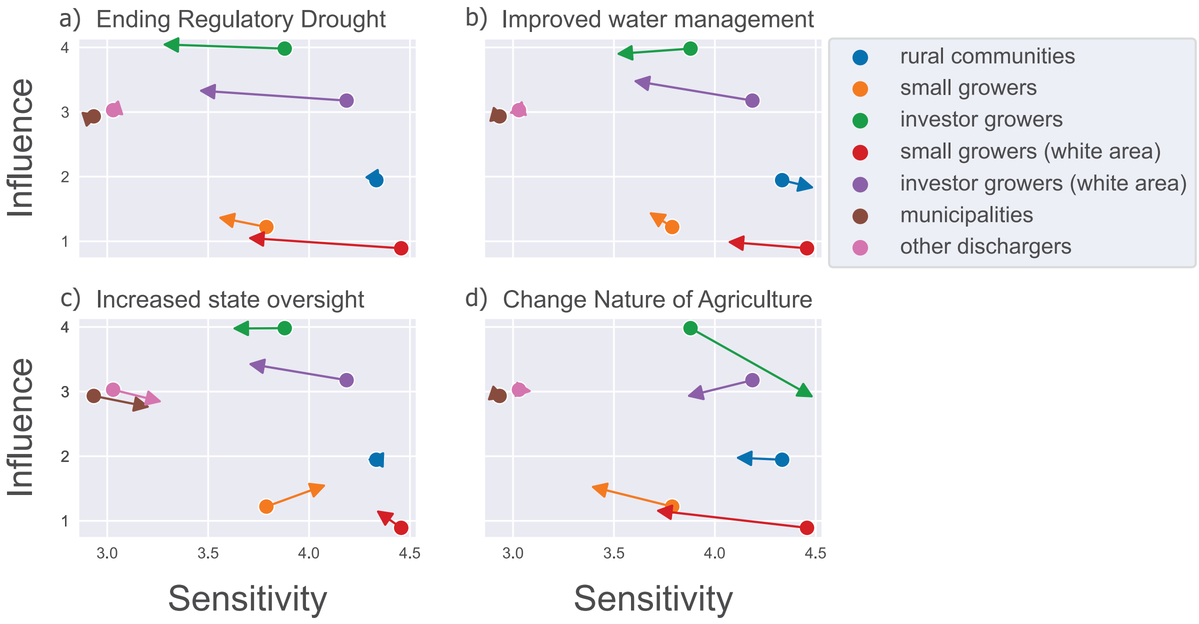

Figure S6: Comparison of each scenario (represented by the arrowhead) with the baseline (the circle). The points represent the average sensitivity and influence over 300 samples. An entities' influence represents how a change in their capacity influences the rest of the system, while their sensitivity represents how a perturbation in the system influences their capacity.

We take as the baseline the system parameterized based on current interactions and (pre-SGMA) policies. An actor's sensitivity is an indication of how strongly their capacity is impacted by changes in the rest of the system, while their influence indicates the impact changes in their capacity have on the system.

As revealed by Figure S6, the provision of additional surface water decreased growers' sensitivities, particularly that of white area growers, making growers more similar in sensitivity to each other. This is unsurprising since the greater sensitivity of white area growers and rural communities in the baseline stems from their having to rely solely on groundwater. We also see an increase in the influence of growers, except for large and investor growers, who were already the most influential. Even though additional surface water benefits rural communities' access to groundwater, these results suggest that this additional water that they have little control over does not significantly reduce their sensitivity to or influence over the governance system. In the second scenario, the introduction of groundwater management under local control similarly decreases the sensitivity of growers, particularly white area growers, though it does not equalize growers with and without surface water access as much as the first scenario does. Despite being a very different scenario, improving water management through farmer-led local governance has a similar effect as the first scenario, not accounting for effects of the first scenario external to the basin, by increasing the availability of water without fundamentally reordering any political or social relationships, mainly benefiting growers.

State control of groundwater management in the third scenario presents a qualitatively different picture, with a decrease in sensitivity for large growers, but an increase in sensitivity for small growers with surface water access. This may be because this scenario involves greater restriction to grower extraction than the second scenario, which disproportionately impacts small growers, who are already more sensitive to changes in water access. For small growers relying solely on groundwater, this increase in sensitivity is mitigated by the benefit of higher groundwater levels, which has a greater impact in reducing their sensitivity than that of growers with surface water access. Interestingly, despite groundwater management not being controlled by local governance organizations with strong representation by growers, as with the second scenario, the influence of all growers except for large growers still increases. This suggests that the increase in influence stems from the increase in groundwater access, an effect that does not seem to extend to rural communities, perhaps because they extract so little that changes in their ability to extract do not change their influence significantly. Interestingly, this scenario is the only one to impact municipalities and other water users by increasing their sensitivity and reducing their influence, likely because of the same restrictions in groundwater use and strengthened water quality regulations that affect growers, but with less of the benefit from increased groundwater levels. Finally, in the last scenario, we see an increase in the sensitivity of large growers with surface water access, and a decrease in sensitivity for other growers. We also see an increase in the influence of smaller growers, and a decrease in the influence of large growers, making this scenario the most equalizing for growers' influences. This is unsurprising because this parameterization reduces large growers' disproportionate water extraction, as well as influence over local governance. This is also the first scenario in which there is a change in rural communities' sensitivity, suggesting that it stems from the relationship between rural communities and small growers, one of the main distinguishing factors between this scenario and the one of increased state oversight.

These scenarios drawn from interviewees' narratives of water governance have important implications for different water users, and reveal the importance of differentiating between water users with fundamentally different relationships with water and governance. However, these results also reveal the changes explored are generally insufficient in fundamentally changing the relative influence of different water users. Even in the final scenario, large growers remain the most influential, and rural communities and small growers the least influential. This suggests that parameters that remained unchanged, namely the sensitivity of different water users' extraction to water availability and their turnover rates, are particularly important in determining influence. These parameters correspond to water users' uneven access to water infrastructure, such as deeper wells, and the social and economic factors that cause small growers to leave farming or rural community residents to leave their communities or otherwise limit their ability to have a sustained voice in governance. Thus, without addressing these asymmetries, much of the fundamental inequity in vulnerability to and power over changes in water and water governance remains.

3.4.5 Heterogeneity within groups

While the different stakeholder groups in the San Joaquin Valley have been grouped as rural community residents, small growers, or large growers in this paper, the interviews revealed that there were important distinctions within these groups that determined how they were impacted by water policies and their ability to engage in water governance. One important distinction was whether a grower was a landowner or leasing the land on which they grew. Organizations working with minority growers, particularly Hmong growers, noted that many of the growers they worked with did not own their land, limiting their ability to put in infrastructure, such as new or deeper wells to replace wells that have run dry, make land-use decisions regarding on-farm recharge, and have formal representation in venues that are limited to land-owners, such as water districts. Finally, the development of water markets threaten to push tenant growers off of the land if water prices are high enough that it is more profitable for landowners to simply sell their water rather than lease their land.

Another important distinction that arose is that between growers for whom farming is their livelihood and farm management companies that manage farms as part of an investment portfolio. While there are no farm managers in the sample, many of the growers and grower advocacy groups interviewed noted that growers struggled with regulatory burden and participating in public meetings in a way that farm management companies, who have the ability to hire staff and consultants to ensure compliance and attend meetings, did not. Growers also noted that investment companies are more easily able to sell or fallow their land if water policies render them no longer profitable, compared to growers for whom selling or fallowing would mean losing their livelihood, and potentially the generational and cultural knowledge associated with having worked that land for multiple generations.

Among community residents, distinctions such as race, socioeconomic status, language, and immigration status played important roles in their ability to engage in governance. Numerous community residents mention incidents where hostility based on their race or speaking Spanish limited their participation in public venues. One interviewee, for example, recalls, "*The lady was very upset that the folks were speaking Spanish and said that this is America you speak English, and so the space is just very hostile to folks*" (Interview 16, community resident). Because many residents of unincorporated communities are undocumented, immigration status was cited as an important factor in whether residents were comfortable seeking help to address drinking water issues in their communities. Such distinctions similarly impact minority growers, whose diverse ethnic backgrounds and languages make it difficult for them to stay aware of regulations that are not always translated into their language, and leads to distrust when interacting with goverment entities due to a history of marginalization. Finally, socioeconomic status determined how different residents were impacted by drinking water issues, influencing their willingness to organize around those issues. One interviewee explains that for residents who are better off socieconomically, "*when we call, and we've done that, their first response is like we have a filter, we're okay or I buy my water so I'm okay. So if they are financially able to do that, their mindset is I'm taken care of, me and my family is take care of so it doesn't matter*" (Focus Group 1, community resident).

While there was not a large enough sample to represent these distinctions in the model, they reinforce the need for disaggregation in understanding the diversity of responses to water management policies.

3.5 Conclusion

We found that four main narratives about water issues and the role of governance in creating, perpetuating, or solving them emerged. Contrary to prior research, there is significant heterogeneity within water user groups, particularly among smaller growers, in their narratives about water governance. Comparing actors' strategies to the ones that maximize their water access reveals how access to resources and knowledge about the system, as well as inherent tradeoffs created by the current governance structure, shape and constrain their strategies. For rural communities and small growers, maximizing water access within the current structure means supporting increased surface water access for the large and investor growers that already extract the most, which means they must pursue more fundamental system transformations to achieve both increased water access and objectives such as sustainability and equity. This conflict between narratives that emphasize environmental justice and the strategy that maximizes their water access, alongside lack of system knowledge, helps explain the gap between actual and "optimal" strategies for small growers and rural communities, as well as the diversity of narratives among small growers ranging from alignment with larger growers over shared goals to direct opposition to their goals and narratives. For large growers who do not face such a conflict and have extensive system knowledge and resources, there tends to be more agreement in their narratives and little difference between their current strategy and the optimal ones. The fact that strategies that optimize water access for multiple water users' also tends to benefit large growers is an indication of their structural power arising from the policies and infrastructure that make up the current regime of water management.

The results regarding the implications of different scenarios for the future of agriculture and water governance offer another perspective on different groups' structural power. The differentiated nature of how water users are impacted by and can influence governance in the different scenarios reveals the importance of disaggregating water users by their differing access to water infrastructure and institutions. In particular, it's clear that increased water access, whether from increased surface water deliveries or improved groundwater management, does not necessarily translate to increased influence over the system or decreased sensitivity, especially for rural communities. Only the fourth narrative, which involved changing the nature of agriculture to reduce the footprint of industrial agriculture and to have a mutually beneficial relationship between communities and growers, reduced the sensitivity of communities. That this narrative remains fairly marginal, espoused only by a few advocacy groups and rural community residents in very general terms, reveals the discursive power of the current agricultural industry in suggesting that the region relies on agriculture in its current form persisting. The results show that such fundamental changes are necessary, however, to ensure that the benefits of alternative resource management regimes are not captured by those that are already the most powerful.

The results of this study are ultimately contingent on the necessarily subjective judgments of how to translate qualitative information to numeric parameters. Drawing from ranges of parameters and modeling ensembles of systems accounts in part for this subjectivity and uncertainty. Similarly, in parameterizing different scenarios, the aim was to translate the changes suggested by different narratives as directly as possible. However, this does not account for how those changes may be tied to others, such as if increased governmental support for small growers reduced their rate of leaving farming or allowed them to install deeper wells. Thus, the results may underestimate some of the changes to influence and sensitivity implied by these narratives.

Nevertheless, this study introduces an approach that, in addition to revealing concrete results about the effects of different interventions for water governance in the San Joaquin Valley, offers broader insight into how system structures generate fundamental disparities in actors' power, the importance of narratives and knowledge in shaping engagement in governance and inspiring groups to forgo short-term interests for visions of broader transformation, and the importance of diverse and tranformative visions for governance in order to create truly equitable systems. It also offers a methodological approach that is readily adaptable to many different contexts, providing a template for models that go beyond positivist and apolitical approaches to explore differentiated impacts and alternative visions for social-ecological systems.

3.6 Appendix

Derivation of Generalized Modeling Scale Parameters

The full mathematical representation of the system is as follows:

$$\dot{R}_1 = S_1(R_1) - \sum_n E_{1,n}(R_1, G_{1,m,n}, \ldots, G_{1,M,n}, \mathbf{E}_{1,k,n}X_k, \ldots, \mathbf{E}_{1,K,n}X_K) - T(R_1, H_m, \ldots, H_M, \mathbf{T}_kX_k, \ldots, \mathbf{T}_K$$

where $G_{1,m,n} = G_{1,m,n}(X_m, \mathbf{G}_{1,a,m,n}X_a, \ldots, \mathbf{G}_{1,A,m,n}X_A)$ and where $H_m = H_m(X_m, \mathbf{H}_{a,m}X_a, \ldots, \mathbf{H}_{A,m}X$

$$\dot{R}_2 = S_2(R_2) - \sum_n E_{2,n}(R_2, E_{1,n}, G_{2,1,n}, \ldots, G_{2,M,n}, \mathbf{E}_{2,k,n}X_k, \ldots, \mathbf{E}_{2,K,n}X_k) + T - L_2(R_2)$$

$$\dot{R}_3 = \frac{1}{R_2}\left[\sum_n D_n(F_{m,n}, \ldots, F_{M,n}, \mathbf{D}_{k,n}X_k, \ldots, \mathbf{D}_{K,n}X_K) - R_3\left[S_2(R_2) + T\right]\right]$$

where $F_{m,n} = F_{m,n}(X_m, \mathbf{F}_{a,m,n}X_a, \ldots, \mathbf{F}_{A,m,n}X_A)$

$$\begin{aligned}\dot{X}_t = &\sum_r B_{r,t}(E_{r,t}) + \sum_a C^+_{a,t}(\mathbf{C}^+_{a,t}X_a) + \sum_m P^+_{m,t}(X_m, \mathbf{P}^+_{a,m,t}X_a, \ldots, \mathbf{P}^+_{A,m,t}X_A) + U^+_t(X_t) \\ &- \sum_a C^-_{a,t}(\mathbf{C}^-_{a,t}X_a) - \sum_m P^-_{m,t}(X_m, \mathbf{P}^-_{a,m,t}X_a, \ldots, \mathbf{P}^-_{A,m,t}X_A) - U^-_t(X_t)\end{aligned}$$

We first define the state variables normalized by their steady state value (R_1^* is the steady state value for R_1, for example):

$$r_k := \frac{R_k}{R_k^*}, \;\; x_n := \frac{X_n}{X_n^*}$$

Resource Equation

We can then write the normalized functions (written for R_1,which can easily be extended to R_2, and R_3):

$$s_1(r_1) := \frac{S_1(r_1R_1^*)}{S_1^*},$$

$$e_{1,n}(r, g_{1,n}, \ldots, g_{M,n}) := \frac{E_{1,n}(rR^*, G^*_{1,n}g_{1,n}, \ldots, G^*_{M,n}g_{M,n}, \mathbf{E}_{1,k,n}x_kX^*_k, \ldots, \mathbf{E}_{1,K,n}x_KX^*_K)}{E^*_{1,n}},$$

where $g_{m,n}(x_m, \mathbf{G}_{1,a,m,n}x_a, \ldots, \mathbf{G}_{1,A,m,n}x_A) := \dfrac{G_{m,n}(x_mX^*_m, \mathbf{G}_{1,a,m,n}x_aX^*_a, \ldots, \mathbf{G}_{1,A,m,n}x_AX^*_A)}{G^*_{m,n}},$

$$t(r_1, H_m, \ldots, H_M, \mathbf{T}_k X_k, \ldots, \mathbf{T}_K X_K) := \frac{T(r_1 R_1^*, H_m^* h_m, \ldots, H_M^* h_M, \mathbf{T}_k x_k X_k^*, \ldots, \mathbf{T}_K X_K^*)}{T^*}$$

where $h_m(x_m, \mathbf{H}_{a,m} x_a, \ldots, \mathbf{H}_{A,m} x_A) := \dfrac{H_m(x_m X_m^*, \mathbf{H}_{a,m} x_a X_a^*, \ldots, \mathbf{H}_{A,m} x_A X_A^*)}{H_m^*}$,

$$l_1(r_1) := \frac{L_1(r_1 R_1^*)}{L_1^*},$$

and

$$d_n(r, f_{m,n}, \ldots, f_{M,n}) := \frac{D_n(rR^*, F_{m,n}^* f_{m,n}, \ldots, F_{M,n}^* f_{M,n}, \mathbf{E}_{1,k,n} x_k X_k^*, \ldots, \mathbf{E}_{1,K,n} x_K X_K^*)}{D_n^*}$$

where $f_{m,n}(x_m, \mathbf{F}_{a,m,n} x_a, \ldots, \mathbf{F}_{A,m,n} x_A) := \dfrac{F_{m,n}(x_m X_m^*, \mathbf{F}_{a,m,n} x_a X_a^*, \ldots, \mathbf{F}_{A,m,n} x_A X_A^*)}{F_{m,n}^*}$.

This allows us to rewrite the equations for $\dot{R}_1$ in terms of the normalized variables and functions:

$$\dot{r_1} = \frac{S_1^*}{R_1^*} s_1 - \sum_n \frac{E_{1,n}^*}{R_1^*} e_{1,n} - \frac{T^*}{R_1^*} t - \frac{L_1^*}{R_1^*} l_1.$$

We then define the *scale parameters:*

$$\phi_1 := \frac{S_1^*}{R_1^*} = \sum_n \frac{E_{1,n}^*}{R_1^*} + \frac{T^*}{R_1^*} + \frac{L_1^*}{R_1^*}$$

$$\psi_1 := \frac{1}{\phi_1} \sum_n \frac{E_{1,n}^*}{R_1^*}$$

$$\widetilde{\psi}_{1,n} := \frac{1}{\phi_1} \frac{1}{\psi_1} \frac{E_{1,n}^*}{R_1^*}$$

$$\overline{\psi}_1 := \frac{1}{\phi_1} \frac{T^*}{R_1^*}$$

$$\widehat{\psi}_1 := \frac{1}{\phi_1}\frac{L_1^*}{R_1^*}$$

Similarly for R_2:

$$\dot{r}_2 = \frac{S_2^*}{R_2^*}s_2 - \sum_n \frac{E_{2,n}^*}{R_2^*}e_{2,n} + \frac{T^*}{R_2^*}t - \frac{L_2^*}{R_2^*}l_2.$$

$$\phi_2 := \frac{S_2^*}{R_2^*} + \frac{T^*}{R_2^*} = \sum_n \frac{E_{2,n}^*}{R_2^*} + \frac{L_2^*}{R_2^*}$$

$$\psi_2 := \frac{1}{\phi_2}\frac{S_2^*}{R_2^*}$$

$$\dddot{\psi}_2 := \frac{1}{\phi_2}\sum_n \frac{E_{2,n}^*}{R_2^*}$$

$$\widehat{\psi}_2 := \frac{1}{\phi_2}\frac{L_2^*}{R_2^*}$$

$$\widetilde{\psi}_{2,n} := \frac{1}{\phi_2}\frac{1}{\dddot{\psi}_2}\frac{E_{2,n}^*}{R_2^*}$$

$$\overline{\psi}_2 := \frac{1}{\phi_2}\frac{T^*}{R_2^*} = \frac{\phi_1}{\phi_2}\frac{R_1^*}{R_2^*}\overline{\psi}_1$$

Since there is clearly a relationship between the proportion of R_1transferred to R_2 ($\overline{\psi}_2$) and the proportion of R_2 that is transferred from $R_1(\overline{\psi}_1)$, $\overline{\psi}_2$ can also be written:

$$\overline{\psi}_2 := \frac{\phi_1}{\phi_2}\frac{R_1^*}{R_2^*}\overline{\psi}_1$$

Finally for R_3:

$$\dot{r}_3 = \frac{1}{r_2}\left[\sum_n \frac{D_n^*}{R_3^*} - r_3\left[\frac{S_2^*(R_2)+T^*}{R_2^*}\right]\right]$$

$$\phi_3 := \frac{\sum_n D_n^*}{R_3^* R_2^*} = \frac{S_2^* + T^*}{R_2^*} = \phi_2$$

$$\widetilde{\psi}_{3,n} := \frac{1}{\phi_2}\frac{D_n^*}{R_3^* R_2^*}$$

$$\psi_3 := \frac{1}{\phi_2}\frac{S_2^*}{R_2^*} = \psi_2$$

$$\overline{\psi}_3 := \frac{1}{\phi_2}\frac{T^*}{R_2^*} = \overline{\psi}_2 = \frac{\phi_1}{\phi_2}\frac{R_1^*}{R_2^*}\overline{\psi}_1$$

Actor Equations

Going through the same process of normalization for the actor equation:

$$\begin{aligned}
b_{t,n}(e_{t,n}) &:= \frac{B_{t,n}(E_{t,n}^* e_{t,n})}{B_{t,n}^*},\\
c_{a,n}^+(\mathbf{C}_{a,n}^+ x_a) &:= \frac{C_{a,n}^+(\mathbf{C}_{a,n}^+ x_a)}{C_{a,n}^{+*}},\ c_{a,n}^-(\mathbf{C}_{a,n}^- x_a) := \frac{C_{a,n}^-(\mathbf{C}_{a,n}^- x_a)}{C_{a,n}^{-*}},\\
p_{a,m,n}^+(x_m, \mathbf{P}_{a,m,n}^+ x_a) &:= \frac{P_{a,m,n}^+(\mathbf{P}_{a,m,n}^+ x_a)}{P_{a,m,n}^{+*}},\ p_{a,m,n}^-(x_m, \mathbf{P}_{a,m,n}^- x_a) := \frac{P_{a,m,n}^-(\mathbf{P}_{a,m,n}^- x_a)}{P_{a,m,n}^{-*}}\\
u_n^+(x_n) &:= \frac{U_n^+(x_n X_n^*)}{U_n^{+*}},\ u_n^-(x_n) := \frac{U_n^-(x_n X_n^*)}{U_n^{-*}}.
\end{aligned}$$

Rewriting $\dot{x}_n$ in terms of the normalized variables and functions:

$$
\begin{aligned}
\dot{x}_n = & \frac{B^*_{1,n}}{X^*_n} b_{1,n} + \frac{B^*_{2,n}}{X^*_n} b_{2,n} + \frac{B^*_{3,n}}{X^*_n} b_{3,n} \\
& + \sum_a \frac{C^{+*}_{a,n}}{X^*_n} c^+_{a,n} + \sum_m \frac{P^{+*}_{m,n}}{X^*_n} p^+_{m,n} + \frac{U^{+*}_n}{X^*_n} u^+_n \\
& - \sum_a \frac{C^{-*}_{a,n}}{X^*_n} c^-_{a,n} - \sum_m \frac{P^{-*}_{m,n}}{X^*_n} p^-_{m,n} - \frac{U^{-*}_n}{X^*_n} u^-_n
\end{aligned}
$$

We can then define the scale parameters:

$$
\alpha_n := \frac{B^*_{1,n}}{X^*_n} + \frac{B^*_{2,n}}{X^*_n} + \frac{B^*_{3,n}}{X^*_n} + \sum_k \frac{C^{+*}_{k,n}}{X^*_n} + \sum_m \frac{P^{+*}_{m,n}}{X^*_n} + \frac{U^{+*}_n}{X^*_n} = \sum_k \frac{C^{-*}_{k,n}}{X^*_n} + \sum_m \frac{P^{-*}_{m,n}}{X^*_n} + \frac{U^{-*}_n}{X^*_n}
$$

$$
\widetilde{\beta}_n := \frac{1}{\alpha_n}\left(\frac{B^*_{1,n}}{X^*_n} + \frac{B^*_{2,n}}{X^*_n} + \frac{B^*_{3,n}}{X^*_n}\right), \quad \widetilde{\sigma}_{r,n} := \frac{1}{\alpha_n}\frac{1}{\widetilde{\beta}_n}\frac{B^*_{r,n}}{X^*_n}
$$

$$
\beta_n := \frac{1}{\alpha_n}\sum_a \frac{C^{+*}_{a,n}}{X^*_n}, \quad \sigma_{a,n} := \frac{1}{\alpha_n \beta_n}\frac{C^{+*}_{a,n}}{X^*_n}
$$

$$
\widehat{\beta}_n := \frac{1}{\alpha_n}\sum_m \frac{P^{+*}_{m,n}}{X^*_n}, \quad \widehat{\sigma}_{m,n} := \frac{1}{\alpha_n \widehat{\beta}_n}\frac{P^{+*}_{m,n}}{X^*_n}
$$

$$
\overline{\beta}_n := \frac{1}{\alpha_n}\frac{U^{+*}_n}{X^*_n}
$$

$$
\eta_n := \frac{1}{\alpha_n}\sum_a \frac{C^{-*}_{a,n}}{X^*_n}, \quad \lambda_{a,n} = \frac{1}{\alpha_n \eta_n}\frac{C^{-*}_{a,n}}{X^*_n}
$$

$$
\widehat{\eta}_n := \frac{1}{\alpha_n}\sum_m \frac{P^{-*}_{m,n}}{X^*_n}, \quad \widehat{\lambda}_{m,n} := \frac{1}{\alpha_n \widehat{\eta}_n}\frac{P^{-*}_{m,n}}{X^*_n}
$$

$$
\overline{\eta}_n := \frac{1}{\alpha_n}\frac{U^{-*}_n}{X^*_n}
$$

Jacobian and Exponent Parameters

From the Resource Equation

We then compute the entries of the Jacobian, which then produces the *exponent parameters*.

For derivatives of resource equations with respect to the resource variables:

$$\frac{\partial \dot{r_1}}{\partial r_1} = \phi_1 \left[\frac{\partial s_1}{\partial r_1} - \psi_1 \sum_n \widetilde{\psi}_{1,n} \frac{\partial e_{1,n}}{\partial r_1} - \overline{\psi}_1 \frac{\partial t}{\partial r_1} \right]$$

$$\frac{\partial \dot{r_2}}{\partial r_1} = \phi_2 \left[\overline{\psi}_2 \frac{\partial t}{\partial r_1} - \sum_n \widetilde{\psi}_{2,n} \frac{\partial e_{2,n}}{\partial e_{1,n}} \frac{\partial e_{1,n}}{\partial r_1} \right]$$

$$\frac{\partial \dot{r_3}}{\partial r_1} = \phi_2 \frac{1}{r_2} \left[r_3 \overline{\psi}_2 \frac{\partial t}{\partial r_1} \right] = \phi_2 \overline{\psi}_2 \frac{\partial t}{\partial r_1}$$

$$\frac{\partial \dot{r_1}}{\partial r_2} = 0$$

$$\frac{\partial \dot{r_2}}{\partial r_2} = \phi_2 \left[\psi_2 \frac{\partial s_2}{\partial r_2} - \sum_n \widetilde{\psi}_{2,n} \frac{\partial e_{2,n}}{\partial r_2} \right]$$

$$\begin{aligned}\frac{\partial \dot{r_3}}{\partial r_2} &= -\phi_2 \frac{1}{r_2^2} \left[\sum \widetilde{\psi}_{3,n} d_n \left(\ldots \right) - r_3 \left[\psi_2 s_2(r_2) + \overline{\psi}_2 t \left(\ldots \right) \right] \right] + \phi_2 \frac{1}{r_2} \left[r_3 \psi_2 \frac{\partial s_2}{\partial r_2} \right] \\ &= -\phi_2 \left[\sum \widetilde{\psi}_{3,n} - \left[\psi_2 + \overline{\psi}_2 \right] \right] + \phi_2 \psi_2 \frac{\partial s_2}{\partial r_2} = \phi_2 \psi_2 \frac{\partial s_2}{\partial r_2}\end{aligned}$$

$$\frac{\partial \dot{r_1}}{\partial r_3} = 0$$

$$\frac{\partial \dot{r_2}}{\partial r_3} = 0$$

$$\frac{\partial \dot{r_3}}{\partial r_3} = \phi_2 \frac{1}{r_2} \left[- \left[\psi_2 s_2(r_2) + \overline{\psi}_2 t\left(\ldots\right) \right] \right]$$

$$= \phi_2 \left[- \left[\psi_2 + \overline{\psi}_2 \right] \right] = \phi_2 \left[- \left[1 \right] \right] = -\phi_2$$

For derivatives of resource equations with respect to the actor capacity variables:

$$\frac{\partial \dot{r_1}}{\partial x_i} = \phi_1 \Bigg[-\psi_1 \sum_n \widetilde{\psi}_{1,n} \left[\frac{\partial e_{1,n}}{\partial (\mathbf{E}_{1,i,n} x_i)} \cdot \mathbf{E}_{1,i,n} + \sum_m \frac{\partial e_{1,n}}{\partial g_{1,m,n}} \cdot \frac{\partial g_{1,m,n}}{\partial (\mathbf{G}_{1,i,m,n} x_i)} \cdot \mathbf{G}_{1,i,m,n} \right] - \overline{\psi}_1 \Bigg[\frac{\partial t}{\partial (\mathbf{T}_i x_i)} \cdot \mathbf{T}_i + \sum_m$$

$$\frac{\partial \dot{r_2}}{\partial x_i} = \phi_2 \Bigg[\overline{\psi}_2 \left[\frac{\partial t}{\partial (\mathbf{T}_i x_i)} \cdot \mathbf{T}_i + \sum_m \frac{\partial t}{\partial h_m} \frac{\partial h_m}{\partial (\mathbf{H}_{i,m} x_i)} \cdot \mathbf{H}_{i,m} \right]$$

$$- \sum_n \widetilde{\psi}_{2,n} \Bigg[\frac{\partial e_{2,n}}{\partial e_{1,n}} \left[\frac{\partial e_{1,n}}{\partial (\mathbf{E}_{1,i,n} x_i)} \cdot \mathbf{E}_{1,i,n} + \sum_m \frac{\partial e_{1,n}}{\partial g_{1,m,n}} \cdot \frac{\partial g_{1,m,n}}{\partial (\mathbf{G}_{1,i,m,n} x_i)} \cdot \mathbf{G}_{1,i,m,n} \right] + \frac{\partial e_{2,n}}{\partial (\mathbf{E}_{2,i,n} x_i)} \cdot \mathbf{E}_{2,i,n} + \sum_m$$

$$\frac{\partial \dot{r_3}}{\partial x_i} = \phi_2 \frac{1}{r_2} \Bigg[\sum_n \widetilde{\psi}_{3,n} \left[\frac{\partial d_n}{\partial (\mathbf{D}_{i,n} x_i)} \cdot \mathbf{D}_{i,n} + \sum_m \frac{\partial d_n}{\partial f_{m,n}} \frac{\partial f_{m,n}}{\partial \mathbf{F}_{i,m,n} x_i} \cdot \mathbf{F}_{i,m,n} \right] - r_3 \overline{\psi}_2 \Bigg[\frac{\partial t}{\partial (\mathbf{T}_i x_i)} \cdot \mathbf{T}_i + \sum_m \frac{\partial t}{\partial h_m} \frac{\partial h}{\partial \mathbf{H}_i}$$

$$= \phi_2 \Bigg[\sum_n \widetilde{\psi}_{3,n} \left[\frac{\partial d_n}{\partial (\mathbf{D}_{i,n} x_i)} \cdot \mathbf{D}_{i,n} + \sum_m \frac{\partial d_n}{\partial f_{m,n}} \frac{\partial f_{m,n}}{\partial \mathbf{F}_{i,m,n} x_i} \cdot \mathbf{F}_{i,m,n} \right] - \overline{\psi}_2 \Bigg[\frac{\partial t}{\partial (\mathbf{T}_i x_i)} \cdot \mathbf{T}_i + \sum_m \frac{\partial t}{\partial h_m} \frac{\partial h_m}{\partial \mathbf{H}_{i,m} x_i}$$

For derivatives of resource equations with respect to decision centers m:

$$\frac{\partial \dot{r_1}}{\partial x_m} = \phi_1 \left[-\psi_1 \sum_n \widetilde{\psi}_{1,n} \frac{\partial e_{1,n}}{\partial g_{1,m,n}} \cdot \frac{\partial g_{1,m,n}}{\partial x_m} - \overline{\psi}_1 \frac{\partial t}{\partial h_m} \frac{\partial h_m}{\partial x_m} \right]$$

$$\frac{\partial \dot{r_2}}{\partial x_m} = \phi_2 \left[\overline{\psi}_2 \frac{\partial t}{\partial h_m} \frac{\partial h_m}{\partial x_m} - \sum_n \widetilde{\psi}_{2,n} \left[\frac{\partial e_{2,n}}{\partial e_{1,n}} \frac{\partial e_{1,n}}{\partial g_{1,m,n}} \cdot \frac{\partial g_{1,m,n}}{\partial x_m} + \frac{\partial e_{2,n}}{\partial g_{2,m,n}} \cdot \frac{\partial g_{2,m,n}}{\partial x_m} \right] \right]$$

$$\begin{aligned}\frac{\partial \dot{r}_3}{\partial x_m} &= \phi_2 \frac{1}{r_2}\left[\sum_n \widetilde{\psi}_{3,n} \cdot \frac{\partial d_n}{\partial f_{m,n}} \cdot \frac{\partial f_{m,n}}{\partial x_m} - r_3 \overline{\psi}_2 \frac{\partial t}{\partial h_m}\frac{\partial h_m}{\partial x_m}\right] \\ &= \phi_2 \left[\sum_n \widetilde{\psi}_{3,n} \cdot \frac{\partial d_n}{\partial f_{m,n}} \cdot \frac{\partial f_{m,n}}{\partial x_m} - \overline{\psi}_2 \frac{\partial t}{\partial h_m}\frac{\partial h_m}{\partial x_m}\right]\end{aligned}$$

From the actor equations

For derivatives of actor equations with respect to resource variables:

$$\frac{\partial \dot{x}_n}{\partial r_1} = \alpha_n \left(\widetilde{\beta}_n \widetilde{\sigma}_{1,n} \frac{\partial b_{1,n}}{\partial e_{1,n}} \cdot \frac{\partial e_{1,n}}{\partial r_1} + \widetilde{\beta}_n \widetilde{\sigma}_{2,n} \frac{\partial b_{2,n}}{\partial e_{2,n}} \cdot \frac{\partial e_{2,n}}{\partial e_{1,n}} \frac{\partial e_{1,n}}{\partial r_1}\right)$$

$$\frac{\partial \dot{x}_n}{\partial r_2} = \alpha_n \left(\widetilde{\beta}_n \widetilde{\sigma}_{2,n} \frac{\partial b_{2,n}}{\partial e_{2,n}} \cdot \frac{\partial e_{2,n}}{\partial r_2}\right)$$

$$\frac{\partial \dot{x}_n}{\partial r_3} = \alpha_n \left(\widetilde{\beta}_n \widetilde{\sigma}_{3,n} \frac{\partial b_{3,n}}{\partial e_{3,n}} \cdot \frac{\partial e_{3,n}}{\partial r_3}\right)$$

For derivatives of actor equations with respect to actor capacity variables:

For $i \neq n$:

$$\begin{aligned}\frac{\partial \dot{x}_n}{\partial x_i} = \alpha_n \Bigg(&\widetilde{\beta}_n \widetilde{\sigma}_{1,n} \frac{\partial b_{1,n}}{\partial e_{1,n}} \cdot \left[\frac{\partial e_{1,n}}{\partial(\mathbf{E}_{1,i,n} x_i)} \cdot \mathbf{E}_{1,i,n} + \sum_m \frac{\partial e_{1,n}}{\partial g_{1,m,n}} \cdot \frac{\partial g_{1,m,n}}{\partial(\mathbf{G}_{1,i,m,n} x_i)} \cdot \mathbf{G}_{1,i,m,n}\right] \\ &+ \widetilde{\beta}_n \widetilde{\sigma}_{2,n} \frac{\partial b_{2,n}}{\partial e_{2,n}} \cdot \Bigg[\frac{\partial e_{2,n}}{\partial(\mathbf{E}_{2,i,n} x_i)} \cdot \mathbf{E}_{2,i,n} + \sum_m \frac{\partial e_{2,n}}{\partial g_{2,m,n}} \cdot \frac{\partial g_{2,m,n}}{\partial(\mathbf{G}_{2,i,m,n} x_i)} \cdot \mathbf{G}_{2,i,m,n} + \frac{\partial e_{2,n}}{\partial e_{1,n}} \cdot \Bigg[\frac{\partial e_{1,n}}{\partial(\mathbf{E}_{1,i,n} x_i)} \cdot \mathbf{E}_{1,i} \\ &+ \widetilde{\beta}_n \widetilde{\sigma}_{3,n} \frac{\partial b_{3,n}}{\partial e_{3,n}} \cdot \left[\frac{\partial e_{3,n}}{\partial(\mathbf{E}_{3,i,n} x_i)} \cdot \mathbf{E}_{3,i,n} + \sum_m \frac{\partial e_{3,n}}{\partial g_{3,m,n}} \cdot \frac{\partial g_{3,m,n}}{\partial(\mathbf{G}_{3,i,m,n} x_i)} \cdot \mathbf{G}_{3,i,m,n}\right] \\ &+ \widehat{\beta}_n \sum_m \widehat{\sigma}_{m,n} \frac{\partial p^+_{m,n}}{\partial(\mathbf{P}^+_{i,m,n} x_i)} \cdot \mathbf{P}^+_{i,m,n} - \widehat{\eta}_n \sum_m \widehat{\lambda}_{m,n} \frac{\partial p^-_{m,n}}{\partial(\mathbf{P}^-_{i,m,n} x_i)} \cdot \mathbf{P}^-_{i,m,n} \\ &+ \beta_n \sigma_{i,n} \frac{\partial c^+_{i,n}}{\partial(\mathbf{C}^+_{i,n} x_i)} \cdot \mathbf{C}^+_{i,n} - \eta_n \lambda_{i,n} \frac{\partial c^-_{i,n}}{\partial(\mathbf{C}^-_{i,n} x_i)} \cdot \mathbf{C}^-_{i,n}\Bigg)\end{aligned}$$

For $i = n$:

$$\begin{aligned}
\frac{\partial \dot{x}_n}{\partial x_n} = \alpha_n \Bigg(& \widetilde{\beta}_n \widetilde{\sigma}_{1,n} \frac{\partial b_{1,n}}{\partial e_{1,n}} \cdot \left[\frac{\partial e_{1,n}}{\partial(\mathbf{E}_{1,n,n} x_n)} \cdot \mathbf{E}_{1,n,n} + \sum_m \frac{\partial e_{1,n}}{\partial g_{1,m,n}} \cdot \frac{\partial g_{1,m,n}}{\partial(\mathbf{G}_{1,n,m,n} x_n)} \cdot \mathbf{G}_{1,n,m,n} \right] \\
& + \widetilde{\beta}_n \widetilde{\sigma}_{2,n} \frac{\partial b_{2,n}}{\partial e_{2,n}} \cdot \left[\frac{\partial e_{2,n}}{\partial(\mathbf{E}_{2,n,n} x_n)} \cdot \mathbf{E}_{2,n,n} + \sum_m \frac{\partial e_{2,n}}{\partial g_{2,m,n}} \cdot \frac{\partial g_{2,m,n}}{\partial(\mathbf{G}_{2,n,m,n} x_n)} \cdot \mathbf{G}_{2,n,m,n} + \frac{\partial e_{2,n}}{\partial e_{1,n}} \cdot \left[\frac{\partial e_{1,n}}{\partial(\mathbf{E}_{1,n,n} x_n)} \cdot \right. \right. \\
& + \widetilde{\beta}_n \widetilde{\sigma}_{3,n} \frac{\partial b_{3,n}}{\partial e_{3,n}} \cdot \left[\frac{\partial e_{3,n}}{\partial(\mathbf{E}_{3,n,n} x_n)} \cdot \mathbf{E}_{3,n,n} + \sum_m \frac{\partial e_{3,n}}{\partial g_{3,m,n}} \cdot \frac{\partial g_{3,m,n}}{\partial(\mathbf{G}_{3,n,m,n} x_n)} \cdot \mathbf{G}_{3,n,m,n} \right] \\
& + \widehat{\beta}_n \sum_m \widehat{\sigma}_{m,n} \frac{\partial p^+_{m,n}}{\partial(\mathbf{P}^+_{n,m,n} x_n)} \cdot \mathbf{P}^+_{n,m,n} - \widehat{\eta}_n \sum_m \widehat{\lambda}_{m,n} \frac{\partial p^-_{m,n}}{\partial(\mathbf{P}^-_{n,m,n} x_n)} \cdot \mathbf{P}^-_{n,m,n} \\
& + \overline{\beta}_n \frac{\partial u^+_n}{\partial x_n} - \overline{\eta}_n \frac{\partial u^-_n}{\partial x_n} \Bigg)
\end{aligned}$$

For derivatives of actor equations with respect to decision center capacity variables:

$$\begin{aligned}
\frac{\partial \dot{x}_a}{\partial x_m} = \alpha_a \Bigg(& \widetilde{\beta}_a \widetilde{\sigma}_{1,a} \frac{\partial b_{1,a}}{\partial e_{1,a}} \cdot \frac{\partial e_{1,a}}{\partial g_{1,m,a}} \cdot \frac{\partial g_{1,m,a}}{\partial x_m} \\
& + \widetilde{\beta}_a \widetilde{\sigma}_{2,a} \frac{\partial b_{2,a}}{\partial e_{2,a}} \cdot \left[\frac{\partial e_{2,a}}{\partial g_{2,m,a}} \cdot \frac{\partial g_{2,m,a}}{\partial x_m} + \frac{\partial e_{2,a}}{\partial e_{1,a}} \cdot \frac{\partial e_{1,a}}{\partial g_{1,m,a}} \cdot \frac{\partial g_{1,m,a}}{\partial x_m} \right] \\
& + \widetilde{\beta}_a \widetilde{\sigma}_{3,a} \frac{\partial b_{3,a}}{\partial e_{3,a}} \cdot \frac{\partial e_{3,a}}{\partial g_{3,m,a}} \cdot \frac{\partial g_{3,m,a}}{\partial x_m} \\
& + \widehat{\beta}_a \widehat{\sigma}_{m,a} \frac{\partial p^+_{m,a}}{\partial x_m} - \widehat{\eta}_a \widehat{\lambda}_{m,a} \frac{\partial p^-_{m,a}}{\partial x_m} \Bigg)
\end{aligned}$$

For decision centers $m \neq j$:

$$\frac{\partial \dot{x}_j}{\partial x_m} = \alpha_j \left(\widehat{\beta}_j \widehat{\sigma}_{m,j} \frac{\partial p^+_{m,j}}{\partial x_m} - \widehat{\eta}_j \widehat{\lambda}_{m,j} \frac{\partial p^-_{m,j}}{\partial x_m} \right)$$

For decision centers $m = j$:

$$\frac{\partial \dot{x}_m}{\partial x_m} = \alpha_m \left(\overline{\beta}_m \frac{\partial u^+_m}{\partial x_m} - \overline{\eta}_m \frac{\partial u^-_m}{\partial x_m} \right)$$

Derivation of Objective Function Gradient

For resource users, their strategy consists of $\mathbf{G}_{r,a,m,n}$ (influencing water supply policy), $\mathbf{F}_{a,m,n}$ (influencing water quality protection policy), $\mathbf{H}_{a,m}$(influencing groundwater recharge policy), and $\mathbf{P}_{a,m,t}$(influencing financial assistance policy). The proportion of their efforts or capacity that they spend on these different strategies must sum to 1:

$$\sum_r \sum_n \sum_m |\mathbf{G}_{r,a,m,n}| + \sum_n \sum_m |\mathbf{F}_{a,m,n}| + \sum_m |\mathbf{H}_{a,m}| + \sum_t |\mathbf{C}_{a,t}| + \sum_t \sum_m |\mathbf{P}_{a,m,t}| = 1$$

n = resource users

k = non-government organizations

m = decision centers / governing organizations

a = actors $(n+k)$

t = all (total) $(n+k+m)$

At equilibrium, the equation

$$\frac{d}{d\mathfrak{p}} \begin{pmatrix} r^* \\ x_n^* \\ y_m^* \end{pmatrix} = -J^{-1} \begin{pmatrix} \frac{\partial \dot{r}}{\partial \mathfrak{p}} \\ \frac{\partial \dot{x}_n}{\partial \mathfrak{p}} \\ \frac{\partial \dot{y}_m}{\partial \mathfrak{p}} \end{pmatrix}$$

describes how the steady state changes with respect to a strategy parameter $\mathfrak{p}$. The following sections show the calculation of the right-hand side of this equation for each of the strategy parameters.

Derivatives with respect to strategy G, at equilibrium

For resources:

$$\frac{\partial \dot{r}_1}{\partial \mathbf{G}_{1,a,m,n}} = -\phi_1 \psi_1 \widetilde{\psi}_{1,n} \cdot \frac{\partial e_{1,n}}{\partial g_{1,m,n}} \cdot \frac{\partial g_{1,m,n}}{\partial (\mathbf{G}_{1,a,m,n} x_a)}$$

$$\frac{\partial \dot{r_2}}{\partial \mathbf{G}_{2,a,m,n}} = -\phi_2 \widetilde{\psi}_{2,n} \cdot \frac{\partial e_{2,n}}{\partial g_{2,m,n}} \cdot \frac{\partial g_{2,m,n}}{\partial (\mathbf{G}_{2,a,m,n} x_a)}$$

$$\frac{\partial \dot{r_2}}{\partial \mathbf{G}_{1,a,m,n}} = -\phi_2 \widetilde{\psi}_{2,n} \cdot \frac{\partial e_{2,n}}{\partial e_{1,n}} \cdot \frac{\partial e_{1,n}}{\partial g_{1,m,n}} \cdot \frac{\partial g_{1,m,n}}{\partial (\mathbf{G}_{1,a,m,n} x_a)}$$

For all other combinations of resources i and j:

$$\frac{\partial \dot{r_i}}{\partial \mathbf{G}_{j,a,m,n}} = 0$$

For actors:

$$\frac{\partial \dot{x}_n}{\partial \mathbf{G}_{1,a,m,n}} = \alpha_n \widetilde{\beta}_n \cdot \left[\widetilde{\sigma}_{1,n} \frac{\partial b_{1,n}}{\partial e_{1,n}} + \widetilde{\sigma}_{2,n} \frac{\partial b_{2,n}}{\partial e_{2,n}} \cdot \frac{\partial e_{2,n}}{\partial e_{1,n}} \right] \cdot \frac{\partial e_{1,n}}{\partial g_{1,m,n}} \cdot \frac{\partial g_{1,m,n}}{\partial (\mathbf{G}_{1,a,m,n} x_a)}$$

$$\frac{\partial \dot{x}_n}{\partial \mathbf{G}_{2,a,m,n}} = \alpha_n \widetilde{\beta}_n \widetilde{\sigma}_{2,n} \cdot \frac{\partial b_{2,n}}{\partial e_{2,n}} \cdot \frac{\partial e_{2,n}}{\partial g_{2,m,n}} \cdot \frac{\partial g_{2,m,n}}{\partial (\mathbf{G}_{2,a,m,n} x_a)}$$

$$\frac{\partial \dot{x}_n}{\partial \mathbf{G}_{3,a,m,n}} = \alpha_n \widetilde{\beta}_n \widetilde{\sigma}_{3,n} \cdot \frac{\partial b_{3,n}}{\partial e_{3,n}} \cdot \frac{\partial e_{3,n}}{\partial g_{3,m,n}} \cdot \frac{\partial g_{3,m,n}}{\partial (\mathbf{G}_{3,a,m,n} x_a)}$$

For all combinations of resource users n and i such that $n \neq i$:

$$\frac{\partial \dot{x}_n}{\partial \mathbf{G}_{1,a,m,i}} = 0$$

Derivatives with respect to strategy E, at equilibrium

For resources:

$$\frac{\partial \dot{r_1}}{\partial \mathbf{E}_{1,k,n}} = -\phi_1 \psi_1 \widetilde{\psi}_{1,n} \cdot \frac{\partial e_{1,n}}{\partial (\mathbf{E}_{1,k,n} x_k)}$$

$$\frac{\partial \dot{r_2}}{\partial \mathbf{E}_{2,k,n}} = -\phi_2 \widetilde{\psi}_{2,n} \cdot \frac{\partial e_{2,n}}{\partial (\mathbf{E}_{2,k,n} x_k)}$$

$$\frac{\partial \dot{r_2}}{\partial \mathbf{E}_{1,k,n}} = -\phi_2 \widetilde{\psi}_{2,n} \cdot \frac{\partial e_{2,n}}{\partial e_{1,n}} \cdot \frac{\partial e_{1,n}}{\partial (\mathbf{E}_{1,k,n} x_k)}$$

For all other combinations of resources i and j:

$$\frac{\partial \dot{r}_i}{\partial \mathbf{E}_{j,k,n}} = 0$$

For actors:

$$\frac{\partial \dot{x}_n}{\partial \mathbf{E}_{1,k,n}} = \alpha_n \widetilde{\beta}_n \cdot \left[\widetilde{\sigma}_{1,n} \frac{\partial b_{1,n}}{\partial e_{1,n}} + \widetilde{\sigma}_{2,n} \frac{\partial b_{2,n}}{\partial e_{2,n}} \cdot \frac{\partial e_{2,n}}{\partial e_{1,n}} \right] \cdot \frac{\partial e_{1,n}}{\partial (\mathbf{E}_{1,k,n} x_k)}$$

$$\frac{\partial \dot{x}_n}{\partial \mathbf{E}_{2,k,n}} = \alpha_n \widetilde{\beta}_n \widetilde{\sigma}_{2,n} \cdot \frac{\partial b_{2,n}}{\partial e_{2,n}} \cdot \frac{\partial e_{2,n}}{\partial (\mathbf{E}_{2,k,n} x_k)}$$

$$\frac{\partial \dot{x}_n}{\partial \mathbf{E}_{3,k,n}} = \alpha_n \widetilde{\beta}_n \widetilde{\sigma}_{3,n} \cdot \frac{\partial b_{3,n}}{\partial e_{3,n}} \cdot \frac{\partial e_{3,n}}{\partial (\mathbf{E}_{3,k,n} x_k)}$$

For all combinations of resource users n and i such that $n \neq i$:

$$\frac{\partial \dot{x}_n}{\partial \mathbf{E}_{3,k,i}} = 0$$

Derivatives with respect to strategy F, at equilibrium

For resources:

$$\frac{\partial \dot{r}_3}{\partial \mathbf{F}_{a,m,n}} = \phi_2 \widetilde{\psi}_{3,n} \cdot \frac{\partial d_n}{\partial f_{m,n}} \cdot \frac{\partial f_{m,n}}{\partial (\mathbf{F}_{a,m,n} x_a)}$$

For all other resources i:

$$\frac{\partial \dot{r}_i}{\partial \mathbf{F}_{a,m,n}} = 0$$

For actors (for any combination of resource users n and i):

$$\frac{\partial \dot{x}_n}{\partial \mathbf{F}_{a,m,i}} = 0$$

Derivatives with respect to strategy D, at equilibrium

For resources:

$$\frac{\partial \dot{r}_3}{\partial \mathbf{D}_{k,n}} = \phi_2 \widetilde{\psi}_{3,n} \cdot \frac{\partial d_n}{\partial (\mathbf{D}_{k,n} x_k)}$$

For all other resources i:

$$\frac{\partial \dot{r}_i}{\partial \mathbf{D}_{k,n}} = 0$$

For actors (for any combination of resource users n and i):

$$\frac{\partial \dot{x}_n}{\partial \mathbf{D}_{k,i}} = 0$$

Derivatives with respect to strategy H, at equilibrium

For resources:

$$\frac{\partial \dot{r}_1}{\partial \mathbf{H}_{a,m}} = -\phi_1 \overline{\psi}_1 \cdot \frac{\partial t}{\partial h_m} \cdot \frac{\partial h_m}{\partial(\mathbf{H}_{a,m} x_a)}$$

$$\frac{\partial \dot{r}_2}{\partial \mathbf{H}_{a,m}} = +\phi_2 \overline{\psi}_2 \cdot \frac{\partial t}{\partial h_m} \cdot \frac{\partial h_m}{\partial(\mathbf{H}_{a,m} x_a)}$$

$$\frac{\partial \dot{r}_3}{\partial \mathbf{H}_{a,m}} = -\phi_2 \overline{\psi}_2 \cdot \frac{\partial t}{\partial h_m} \cdot \frac{\partial h_m}{\partial(\mathbf{H}_{a,m} x_a)}$$

For actors:

$$\frac{\partial \dot{x}_n}{\partial \mathbf{H}_{a,m}} = 0$$

Derivatives with respect to strategy T, at equilibrium

For resources:

$$\frac{\partial \dot{r}_1}{\partial \mathbf{T}_k} = -\phi_1 \overline{\psi}_1 \cdot \frac{\partial t}{\partial(\mathbf{T}_k x_k)}$$

$$\frac{\partial \dot{r}_2}{\partial \mathbf{T}_k} = +\phi_2 \overline{\psi}_2 \cdot \frac{\partial t}{\partial(\mathbf{T}_k x_k)}$$

$$\frac{\partial \dot{r}_3}{\partial \mathbf{T}_k} = -\phi_2 \overline{\psi}_2 \cdot \frac{\partial t}{\partial(\mathbf{T}_k x_k)}$$

For actors:

$$\frac{\partial \dot{x}_n}{\partial \mathbf{T}_k} = 0$$

Derivatives with respect to strategy C, at equilibrium

For resources:

$$\frac{\partial \dot{r}_i}{\partial \mathbf{C}_{a,t}} = 0$$

For actors and governing orgs:

$$\frac{\partial \dot{x}_t}{\partial \mathbf{C}^+_{a,t}} = \alpha_t \beta_t \sigma_{a,t} \cdot \frac{\partial c^+_{a,t}}{\partial (\mathbf{C}^+_{a,t} x_a)}$$

$$\frac{\partial \dot{x}_t}{\partial \mathbf{C}^-_{a,t}} = \alpha_t \eta_t \lambda_{a,t} \cdot \frac{\partial c^-_{a,t}}{\partial (\mathbf{C}^-_{a,t} x_a)}$$

For all combinations of actors or governing orgs t and i such that $t \neq i$:

$$\frac{\partial \dot{x}_t}{\partial \mathbf{C}^\pm_{a,i}} = 0$$

Derivatives with respect to strategy P, at equilibrium

For resources:

$$\frac{\partial \dot{r}_i}{\partial \mathbf{P}_{a,m,t}} = 0$$

For actors:

$$\frac{\partial \dot{x}_t}{\partial \mathbf{P}^+_{a,m,t}} = \alpha_t \widehat{\beta}_t \widehat{\sigma}_{m,t} \cdot \frac{\partial p^+_{m,t}}{\partial (\mathbf{P}^+_{a,m,t} x_a)}$$

$$\frac{\partial \dot{x}_t}{\partial \mathbf{P}^-_{a,m,t}} = \alpha_t \widehat{\eta}_t \widehat{\lambda}_{m,t} \cdot \frac{\partial p^-_{m,t}}{\partial (\mathbf{P}^-_{a,m,t} x_a)}$$

For all combinations of actors or governing orgs t and i such that $t \neq i$:

$$\frac{\partial \dot{x}_t}{\partial \mathbf{P}^\pm_{a,m,i}} = 0$$

Calculating how objective functions change with each parameter

For $e_{1,n}$ **and** $e_{3,n}$ General formula:

$$\frac{de_{1,n}}{d\mathfrak{p}} = \frac{\partial e_{1,n}}{\partial r_1}\frac{\partial r_1^*}{\partial \mathfrak{p}} + \sum_m \left(\frac{\partial e_{1,n}}{\partial g_{1,m,n}}\frac{\partial g_{1,m,n}}{\partial x_m}\frac{\partial x_m^*}{\partial \mathfrak{p}} + \sum_a \frac{\partial e_{1,n}}{\partial g_{1,m,n}}\frac{\partial g_{1,m,n}}{\partial(\mathbf{G}_{1,a,m,n}x_a)}\frac{\partial x_a^*}{\partial \mathfrak{p}}\mathbf{G}_{1,a,m,n} \right) + \sum_k \frac{\partial e_{1,n}}{\partial(\mathbf{E}_{1,k,n}x_k)}\frac{\partial x_k^*}{\partial \mathfrak{p}}$$

This applies to $\frac{de_{q,n}}{d\mathbf{G}_{r,l,j,i}}$ with resource users $i \neq n$ (any government org j, actor l), $\frac{de_{1,n}}{d\mathbf{E}_{1,l,i}}$ with resource users $i \neq n$ (any non-governing org l), and all other strategy parameters.

We get extra terms in a couple of cases.

For resource users $i = n$, resource $q = r$, government org j, actor l:

$$\frac{de_{r,n}}{d\mathbf{G}_{r,l,j,n}} = [\text{everything from general formula}] + \frac{\partial e_{r,n}}{\partial g_{r,j,n}}\frac{\partial g_{r,j,n}}{\partial(\mathbf{G}_{r,l,j,n}x_l)}$$

For resource users $n = n$, non-governing org l:

$$\frac{de_{r,n}}{d\mathbf{E}_{r,l,n}} = [\text{everything from general formula}] + \frac{\partial e_{r,n}}{\partial(\mathbf{E}_{r,l,n}x_l)}$$

For $e_{2,n}$ General formula:

$$\frac{de_{2,n}}{d\mathfrak{p}} = \frac{\partial e_{2,n}}{\partial r_2}\frac{\partial r_2^*}{\partial \mathfrak{p}} + \frac{\partial e_{2,n}}{\partial e_{1,n}}\frac{de_{1,n}}{d\mathfrak{p}} + \sum_m \left(\frac{\partial e_{2,n}}{\partial g_{2,m,n}}\frac{\partial g_{2,m,n}}{\partial x_m}\frac{\partial x_m^*}{\partial \mathfrak{p}} + \sum_a \frac{\partial e_{2,n}}{\partial g_{2,m,n}}\frac{\partial g_{2,m,n}}{\partial(\mathbf{G}_{2,a,m,n}x_a)}\frac{\partial x_a^*}{\partial \mathfrak{p}}\mathbf{G}_{2,a,m,n} \right) + \sum_k$$

Note that e_3 works like e_1. For e_2, first compute $\frac{de_{1,n}}{d\mathfrak{p}}$, $\frac{de_{2,n}}{d\mathfrak{p}}$, and $\frac{de_{3,n}}{d\mathfrak{p}}$ as above. Then correct $\frac{de_{2,n}}{d\mathfrak{p}}$ by doing:

$$\frac{de_{2,n}}{d\mathfrak{p}} = [\text{calculation using } R_1 \text{ formula, including special cases}] + \frac{\partial e_{2,n}}{\partial e_{1,n}}\frac{de_{1,n}}{d\mathfrak{p}}$$

	Ending the “regulatory drought”	Improved water management	Increased state oversight	Change the nature of agriculture
rural communities	0.0666	0.0555	0.9179	0.6072
small growers	**0.0008**	**5.2552e-06**	**5.2632e-11**	**6.0273e-09**
investor growers	0.1909	0.1747	0.9434	**2.7808e-45**
small growers (white area)	**0.0008**	**0.0084**	**1.3368e-12**	**1.3298e-10**
investor growers (white area)	**0.0029**	**4.613e-07**	**3.5731e-05**	**6.2089e-05**
municipalities	0.1561	0.5350	0.0018	0.5377
other dischargers	0.1128	0.1927	0.0011	0.5809

Table 3.2: T-test results for whether difference in influences between baseline and new scenario are significant (two-sided t-test). Cases in which result is significant ($p<0.005$) are highlighted.

Sensitivity and Influence Calculations

The approach for computing the sensitivity and influence of different system components is introduced by Aufderheide et al., 2013. The sensitivity of entity i,Se_i, is computed as

$$\mathrm{Se_i} = \log(-\sum_k \frac{|v_i^k|}{\lambda_k})$$

where $|v_i^k|$is the absolute value of the entry v_i of the kth right eigenvector and λ_k is the corresponding eigenvalue. Similarly, the influence of entity i is computed as

$$\mathrm{In}_i = \log\left(-\sum_k \frac{|w_i^k|}{\lambda_k}\right)$$

where $|w_i^k|$is the absolute value of the entry w_i of the kth left eigenvector. This calculation is only meaningful in stable systems, so unstable systems are filtered out before the sensitivity and influence metrics are computed.

Supplementary Results

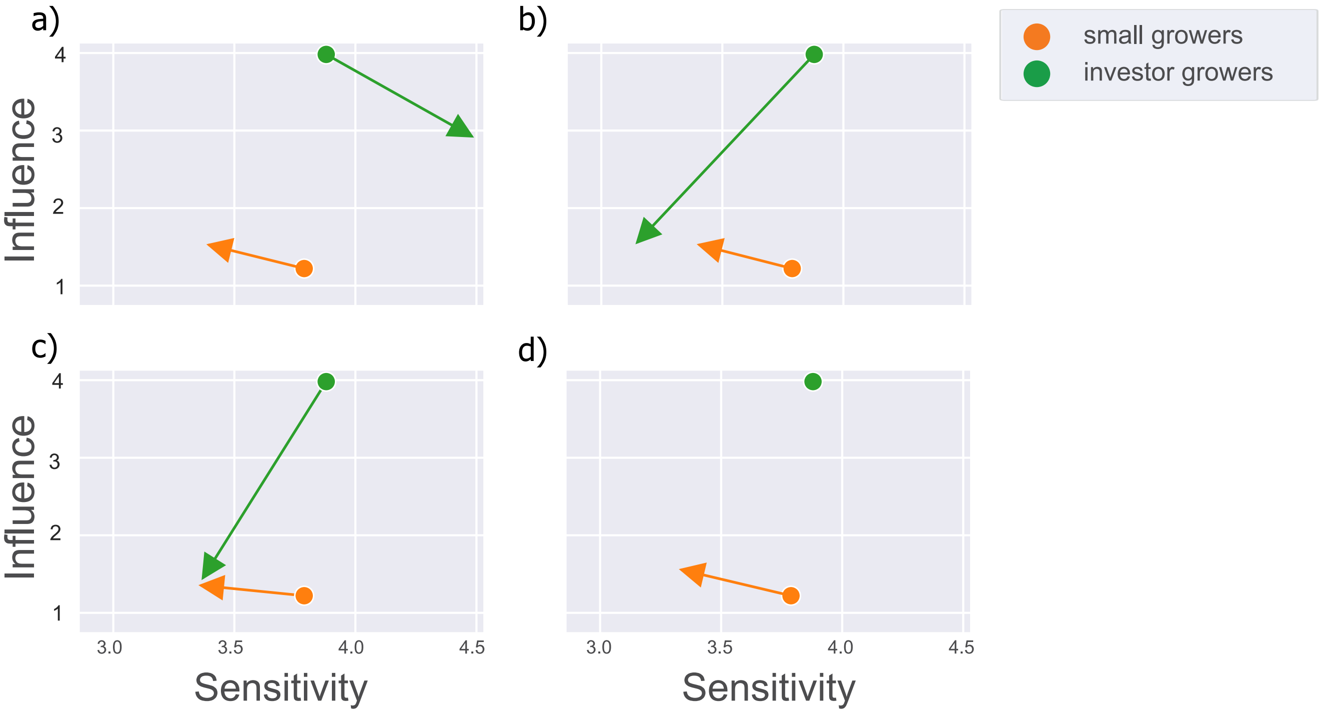

Figure S7: Variations on “Change Nature of Agriculture” scenario (Figure 4(d) in paper). a) The original scenario, which has turnover rate (α) and sensitivity of extraction to water availability ($\partial e/\partial r$) higher on average for small growers (as is the case with the other scenarios). All other parameters sampled from the same range for small and large growers. b) α set the same for small and large growers, $\partial e/\partial r$ higher for small growers, c) α and $\partial e/\partial r$ the same on average for small and large growers (leading to the same influence and sensitivity), and d)$\partial e/\partial r$ set the same for small and large growers, α higher for small growers

	Ending the "regulatory drought"	Improved water management	Increased state oversight	Change the nature of agriculture
rural communities	0.5934	0.1008	0.5402	**0.0247**
small growers	0.0556	0.1260	**0.0006**	**1.59E-05**
investor growers	**1.03E-10**	**0.0002**	**0.0069**	**3.91E-11**
small growers (white area)	**1.07E-15**	**6.92E-05**	**0.2085**	**6.20E-13**
investor growers (white area)	**4.82E-18**	**5.69E-13**	**2.00E-09**	**2.28E-06**
municipalities	0.1561	0.4412	**1.27E-07**	0.5705
other dischargers	0.1128	0.1927	**5.16E-06**	0.1646

Table 3.3: T-test results for whether difference in sensitivities between baseline and new scenario are significant (two-sided t-test). Cases in which result is significant ($p<0.05$) are highlighted.

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