Robustness of social-ecological system under global change:

Insights from community irrigation and forestry systems

by

Jae Hoon David Yu

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Graduate Supervisory Committee:

John M. Anderies, Chair
Marcus A. Janssen
Rachata Muneepeerakul

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ABSTRACT

Social-ecological systems (SES) are replete with hard and soft human-made components (or infrastructures) that are consciously-designed to perform specific functions valued by humans. How these infrastructures mediate human-environment interactions is thus a key determinant of many sustainability problems in present-day SES. This dissertation examines the question of how some of the designed aspects of physical and social infrastructures influence the robustness of SES under global change. Due to the fragility of rural livelihood systems, locally-managed common-pool resource systems that depend on infrastructure, such as irrigated agriculture and community forestry, are of particular importance to address this sustainability question. This dissertation presents three studies that explored the robustness of communal irrigation and forestry systems to economic or environmental shocks. The first study examined how the design of irrigation infrastructure affects the robustness of system performance to an economic shock. Using a stylized dynamic model of an irrigation system as a testing ground, this study shows that changes in infrastructure design can induce fundamental changes in qualitative system behavior (i.e., regime shifts) as well as altered robustness characteristics. The second study explored how connectedness among social units (a kind of social infrastructure) influenced the post-failure transformations of large-N forest commons under economic globalization. Using inferential statistics, the second study argues that some attributes of the social connectedness that helped system robustness in the past made the system more vulnerable to undesirable transformations in the current era. The third study explored the question of how to guide adaptive management of SES for more robustness under uncertainty. This study used an existing laboratory behavioral experiment in which human-subjects tackle a decision problem on collective management of an irrigation system under environmental uncertainty. The contents of group communication and the decisions of individuals were analyzed to understand how configurations of learning-by-doing and other adaptability-related conditions may be causally linked to robustness under environmental uncertainty. The results show that robust systems are characterized by two conditions: active learning-by-doing through outer-loop processes, i.e., frequent updating of shared assumptions or goals that underlie specific group strategies, and frequent monitoring and reflection of past outcomes.

DEDICATION

To my wife, Young Nim Ko, and our parents, siblings, and extended family members who have been patient with me and supported me. Above all, I thank the Lord.

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TABLE OF CONTENTS

Page

APPENDIX

LIST OF TABLES

Table Page

Table Page

LIST OF FIGURES

Figure Page

LIST OF PAPERS

This doctoral thesis is based on the following three manuscripts (one published and two working papers).

CHAPTER 2:

Yu, D. J., M. R. Qubbaj, R. Muneepeerakul, J. M. Anderies, and R. Aggarwal. 2014. The effect of infrastructure design on social-ecological system dynamics: Maintenance thresholds and asymmetric access. *CBIE Working Paper Series*. Tempe, AZ.

CHAPTER 3:

Yu, D. J., J. M. Anderies, D. Lee, and I. Perez. 2014. Transformation of resource management institutions under globalization: The case of songgye community forests in South Korea. *Ecology and Society* 19.

CHAPTER 4:

Yu, D. J., H. C. Shin, I. Pérez, et al. 2015. Demystifying building blocks of adaptive management of social-ecological system under uncertainty : Evidence from a behavioral experiment. Tempe, AZ. (manuscript).

1. INTRODUCTION

1.1. Introduction

Resources held in common, or common-pool resources (CPR), play an important role in supporting the livelihoods of countless rural populations (Jodha 1990). The world is filled with cases of social-ecological systems (SES) in which CPR are actively used and managed to support the local livelihoods. Such systems include, for example, irrigated agriculture (Siy 1980, Wade 1988a), community forestry (McKean 1986), and coastal fisheries (Acheson 1988). It is important to note that, in these critical systems, humans do not interact with their resource base directly. Instead, these interactions are mediated by some kind of human-made components (or infrastructures) that are consciously designed to perform specific functions valued by humans (Anderies et al. 2004).

For example, in many agricultural systems, humans build and maintain *hard human-made infrastructure* such as canals and dams to obtain a steady supply of water resources. This physical infrastructure enables humans to expand and stabilize agricultural production levels despite fluctuations in natural water availability. Further, humans often craft and deploy *soft human-made infrastructure*, such as institutional arrangements and organizational forms, to govern a SES. This type of social infrastructure brings order and regularity to human interactions with resource systems, as well as to human behavior to each other, and thus facilitates collective action (North 1990). In short, many SES (particularly those in which CPR are managed) are partially designed or engineered with some kind of physical and social infrastructures that intervene how humans interact with the environment.

Furthermore, the current era has witnessed the deepening of global change that generates high degrees of complexity and uncertainty in the dynamic elements of SES (Dietz et al. 2003, Polasky et al. 2011). Economic globalization and global environmental change have brought profound changes on the challenges faced by locally-managed SES (Young et al. 2006, Adger et al. 2009). How these novel conditions affect feedbacks among SES components, such as resource systems, human behavior and society, and physical and social infrastructures, are poorly understood (Brashares 2010). Given these trends, a sustainability question of great importance is: **how infrastructure (and its design) shape the dynamics of SES in the face of global change-induced disturbances.**

In this thesis, I explore this broad question using examples of communal irrigation and forestry systems as a testing ground. Note that the role of infrastructure is clearly present in these exemplary systems. Specifically, I study the dynamics of these systems in the context of the *collective action problems* associated with the maintenance of infrastructure and the appropriation of CPR (Ostrom et al. 1994, Dayton-Johnson 2003). Further, I focus on one particular aspect of system dynamics—*robustness* of system performance under collective action problems and global change. Robustness, which is conceptually similar to engineering resilience (Holling and Meffe 1996) and specified resilience (Carpenter et al. 2001, Folke et al. 2010), relates to the sensitivity or resistance of some desired system outputs to disturbances (Carlson and Doyle 2002, Csete and Doyle 2002). Both concepts of robustness and resilience concern some aspects of ability to maintain desired system characteristics or function despite fluctuations in the behavior of its internal parts or external environment (Folke 2006, Anderies et al. 2013b). I favor the use of robustness throughout this thesis because it is more in line with how designed systems withstand shocks and maintain functions, compared to resilience (Janssen and Anderies 2013).

This thesis progresses through the following chapters. In **Chapter 2**, I used a dynamic model of a farmer-managed irrigation system to explore how design variations in physical infrastructure may induce regime shifts and altered robustness characteristics in the model system. Specifically, I examined the effects of two designed features—threshold of infrastructure maintenance and asymmetric access to irrigation water—on the long-term dynamics of the model irrigation system.

In **Chapter 3**, I explored the effect of organizational form or social connectedness (a kind of social infrastructure) on the robustness and transformability of self-governed forest commons. I conducted secondary analysis using an existing case study data of 89 self-governed forest commons (Kang 2001) to study the effect of the social infrastructure. These self-governed systems developed an intricate web of connectedness among social units to implement nested enterprises (Ostrom 1990). I investigated how some of the designed aspects of the nested enterprises influenced the trajectories of SES transformation under economic globalization.

In **Chapter 4**, I researched the question of how to guide adaptive management of an infrastructure-dependent SES under environmental uncertainty. To tackle this puzzle, I used an existing laboratory behavioral experiment (Anderies et al. 2013a) in which human-subjects face a set of decision problems on collective management of an irrigation infrastructure under environmental uncertainty. By examining the iterated decision-making and learning processes undergone by the human-subjects, I tried to uncover configurations of learning processes and supporting conditions that may be causally linked to system robustness.

Finally, in **Chapter 5**, I synthesize my research findings, and then reflect on what could be design criteria of physical and social infrastructure for more robust SES. In the remainder of this introductory chapter, I introduce some of the key concepts that are often referred to throughout the thesis: robustness of social-ecological system, notable frameworks and system-level properties related to SES dynamics (the Robustness framework, the SES framework, resilience, robustness, and resilience engineering), and collective action and self-governance of the commons.

1.2. Robustness of social-ecological system

The social-ecological systems approach (Berkes et al. 2003) and the similar lines of thinking (Turner et al. 2003, Liu et al. 2007) have received much scholarly attention in the recent years. These approaches have helped us better understand complex patterns and feedbacks not evident when ecological systems or social systems are studied separately. In this thesis, I adopt a definition of social-ecological system developed by Anderies et al. (2004): "the subset of social systems in which some of the interdependent relationships among humans are mediated through interactions with biophysical and non-human biological units". Social-ecological system (SES) is a kind of complex adaptive system that can self-organize and adapt in a changing environment (Levin and Clark 2010, Levin et al. 2012). It is composed of multiple components (e.g., natural system, individuals and their behavior, and physical and social infrastructures) that locally interact to generate system-level dynamics that are often emergent and unpredictable. Throughout the thesis, I focus on a particular kind of SES—*highly-engineered* or *infrastructure-dependent* SES in which the role of physical infrastructure, social infrastructure, or both is clearly present.

Managing an infrastructure-dependent SES through global change is a task riddled with an irreducible amount of uncertainty in coupled social and ecological processes. Change and surprise are inevitable because components of SES often interact across scales and levels of organization (Holling and Meffe 1996, Gallopin et al. 2001, Berkes 2007). It is thus impossible to know in advance all disturbances that threaten a SES and their probabilities, and to be prepared for them through preemptive measures (Polasky et al. 2011). **Hence, a critical challenge for sustainability is how we can facilitate the capacity of an infrastructure-dependent SES to maintain their functions in the face of unexpected and emergent threats**.

Due to the fragility of rural livelihood SES, communal systems of natural resources that depend on infrastructure, such as irrigated agriculture and community forestry, are of particular importance to address this sustainability challenge. A major kind of threat faced by these systems is collective action problems—a conflict between individual and group-level interests (Olson 1965, Sandler 1992, Kollock 1998). For example, farmers in irrigation communities of the developing world often face collective action problems associated with infrastructure maintenance and resource appropriation (Ostrom 1990). Because it is often difficult to exclude non-contributors of infrastructure maintenance from deriving benefits from the infrastructure, the problem of free-riding can spread and hinder adequate maintenance of infrastructure. Moreover, one person's consumption of resources often leads to a reduced amount of the resources available to others. Benefits of excessive resource consumption by one individual solely accrue to that individual, while associated negative effects (e.g., resource depletion) are shared by all others (negative externality). In this type of circumstances, self-interested rational actors would make behavioral choices that constrain positive externality (under-provision of infrastructure from free-riding) and foster negative externality (resource degradation or depletion from over-use of resources).

On top of the collective action problems, global change driven by climate change and economic globalization has had significant effects on the sustainability of communal systems of natural resources and people's livelihoods (e.g., O'Brien and Leichenko 2000, Adger et al. 2009). For example, as economic globalization deepens, users will likely gain more exit options to their traditional livelihood dependence on CPR: an increased availability of substitute goods (e.g., imported oil and coal replacing firewood) or new livelihood opportunities (e.g., Baker 1997, Adams et al. 1997). Economic value of CPR will likely be less salient in such situations, and this will, in turn, weaken the incentives for collective action (Basurto and Ostrom 2009). Further, impacts of climate change are becoming more apparent around the world on ecosystem structure and function (Walther et al. 2002, Grimm et al. 2013), global food production (Parry et al. 2004), and human health (Patz et al. 2005). Under these novel conditions, communal SES with existing physical and social infrastructures may be stretched beyond their capacity to perform and maintain their intended functions on their own. To sum it up, in the current era of global change, infrastructure-dependent SES have to deal with multiple stressors that originate from collective action problems, economic globalization, and climate change.

Building on the above discussion, I tackle the following specific questions related to the robustness of infrastructure-dependent SES. **First, how designed aspects of physical infrastructure or organizational form affect the incentives that users face in collective action problems associated with infrastructure maintenance and resource appropriation and how such effects, in turn, influence the robustness of SES to globalization and climate change-related disturbances?** This question is important because, although much understanding has been gained on the design of institutional arrangements linked to collective action, we still do not know enough about the effect of physical infrastructure design and organizational form on the robustness of SES. **Second, in the face of uncertainty, how can we guide adaptive management of infrastructure-dependent SES for more robustness?** This question attempts to address a long-standing research problem in the field of adaptive management of natural resources. Adaptive management is a learning-focused approach in which resource managers engage in iterated decision-making and learning to manage their resource system through uncertainty (Walters and Holling 1990). Although the concept of adaptive management of natural resources has been around for more than three decades, the evidence in support of the approach does not show what type of learning process is most effective and under what conditions for success (Biggs et al. 2012, Fabricius and Cundill

2014). More nuanced understanding is needed on what characterizes configurations of learning process and underlying conditions that may be causally linked to robustness under uncertainty.

1.3. Frameworks, resilience, and robustness.

To study the dynamics of SES over time, it is useful to have a conceptual framework that organizes key components and interactions within SES, as well as a system-level property that represents how well a SES can maintain its function in the face of change. Some of the notable frameworks for this purpose include the SES Framework (Ostrom 2007, 2009) and the Robustness Framework (Anderies et al. 2004), among others. Two system-level properties are widely cited in the SES-related literature: resilience as developed in ecology and the SES research (Holling 1973, Walker et al. 2004) and in safety management of built systems (Hollnagel 2014) and robustness as developed in robust control of feedback systems (Csete and Doyle 2002, Anderies et al. 2004). There is also the concept of vulnerability, which can be thought of as the opposite of resilience or robustness (Folke et al. 2002) or "a function of the exposure of a system and its sensitivity to stress, shocks, and adverse change, and its capacity to cope with and adapt to such disturbances" (Adger et al. 2009). In the SES literature, vulnerability is typically used in the context of *household-level* capacity to maintain livelihoods in the face of disturbances (Adger 2006). Since I am more interested in the *system-level* dynamics of SES, vulnerability will only be sparsely discussed throughout the thesis.

1.3.1. The Robustness framework

The Robustness Framework emphasizes infrastructure-related aspects of SES. As shown in Figure 1.1, it conceptualizes a SES as an aggregate of four main components: resource, resource users, public infrastructure, and public infrastructure providers. The key interactions among the four components can be summarized as follows. Resource is appropriated by resource users (link 1). Resource users build and maintain some kind of public infrastructure (link 6). This infrastructure can be either hard human-made infrastructure such as dams and canals that makes resources available for appropriation by resource users (link 4) or soft human-made infrastructure such as social institutions that intervenes how resource users appropriate resources (link 5). Moreover, not all of the resource users may be involved in maintaining the public infrastructure. There may exist a separate entity (public infrastructure provider) such as a government agency that interacts with resource users (link 2) and produces public infrastructure (link 3). The four components are also exposed to disturbances from outside. Social, economic, or political disturbances (link 8) such as economic development and political regime changes can affect resource users and public infrastructure providers. Biophysical disturbances (link 7) such as climate variability and natural disasters affect resource and public infrastructure. Taken together, these components and interactions provide a useful common vocabulary or meta-theoretical common language that we can use to study the dynamics of SES under collective action problems and biophysical and socioeconomic disturbances.

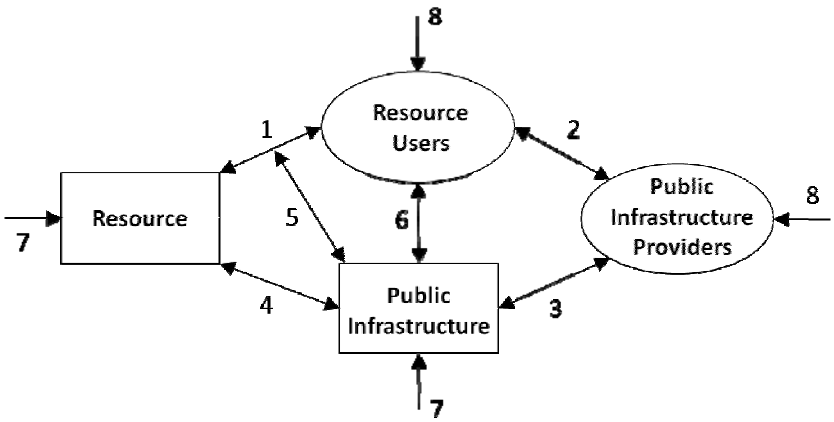

Figure 1.1. Key components and interactions of the Robustness framework. This is an adaption from Anderies et al. (2004).

1.3.2. The SES framework

The SES Framework emphasizes the multi-tiered structure and a host of contextual factors that characterize a SES. It is an outgrowth of the Institutional Analysis and Development (IAD) framework (Kiser and Ostrom 1982, Oakerson 1992). The SES framework expanded the biophysical context of the action arena left largely unexplored by the IAD framework (Ostrom 2011). The framework offers a meta-theoretical common language that provides a general set of contextual factors and general relationships among them for studying the dynamics of SES. In the framework, actors interact in an action situation and generate outcomes. These processes are affected by and affect the four main components of the framework: resource system, resource units, governance system, and users. Outside influences of social, economic, and political settings and related ecosystems also affect the four components and vice versa. Each main component contains detailed attributes in the lower tier, which may then be expanded recursively into another lower tier with more detailed attributes. Thus, the SES Framework is both ontological and diagnostic (Poteete et al. 2010). It is ontological in the sense that it views a SES as a system within another system in hierarchy (thus, elegantly capturing the complexity of SES). It is also diagnostic because it allows institutional analysts to pinpoint an appropriate level of system and attributes for diagnosing problems.

1.3.3. Resilience of SES

Two system-level properties are often used to study the persistence of SES in the face of change: resilience and robustness. Resilience, rooted in ecology (Holling 1973), is a cluster of concepts that has recently expanded to study how SES persist and transform among multiple regimes of self-organizing processes: resilience as persistence, adaptability, and transformability (Walker et al. 2004, Carpenter and Brock 2008, Folke et al. 2010). It is formally defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure and feedbacks, and therefore identity " (Folke et al. 2010). Resilience can be further classified into general resilience and specified resilience (Carpenter et al. 2001, Folke et al. 2010). General resilience refers to the general capacity of a system to deal with all kinds of disturbances, both expected and unexpected ones. Hence, adaptability and transformability are important elements for general resilience. Specified resilience, in contrast, is about "resilience of what to what" (Carpenter et al. 2001). It focuses on the capacity of a system to maintain a specific function in relation to a particular disturbance. At its core, resilience thinking is about the aspects of self-organizing processes that generate multiple regimes (also referred to as stable attractors or basins of attraction), thresholds that divide those regimes, and how critical transitions may occur among them from a seeming small change in a variable (regime shift). Finally, resilience by itself does not address normative considerations. That is, a regime, whether good or bad to human well-being, can be still resilient. In short, resilience thinking highlights endogenous processes that generate multiple regimes and does not address normative considerations that may be central to SES managed by humans for a purpose.

Consider the cases of intentionally-designed SES that are with little endogenous processes and are invariable in short to medium run. How can we identify thresholds and multiple stable attractors for them? How can we conceptualize adaptability and transformability in such invariable, designed systems? Because of ambiguities of resilience ideas in relation to these questions, some scholars have argued that resilience is conceptually difficult to apply to SES that are designed with human intent to perform specific functions (Anderies et al. 2004, Janssen and Anderies 2013, Krupa et al. 2014). This argument motivates us to consider another system-level property that we can use to study the persistence of SES in the face of change, i.e., robustness.

1.3.4. Robustness of SES

Robustness, rooted in engineering, relates to the sensitivity of some desired system outputs to internal or external perturbations (Carlson and Doyle 2002, Csete and Doyle 2002). Application of robustness ideas to a system requires a precise definition of system boundary and at least one output or performance measure (Anderies et al. 2013b). Robustness is a disturbance-specific concept; it represents a degree of resistance relative to a particular disturbance. Hence, application of robustness ideas leads us to consider potential tradeoffs in robustness of a system output to different disturbances that may occur as a result a design change.

Inspired by the work of theoretical engineers on robustness and robust control of feedback systems, a group of SES scholars have extended the concept of robustness to the study of SES (Anderies et al. 2004, Lam 2006, Shivakoti and Bastakoti 2006, Krupa et al. 2014). Their rationale for the adoption of robustness is that many SES contain human-made components that are designed to help maintain system performance in the face of some variability, a prime example of which is irrigation infrastructure (Anderies et al. 2013b, Janssen and Anderies 2013). In a typical farmer-managed irrigation system, farmers sense outcomes and conditions (e.g., water availability) and then dynamically adjust their infrastructure maintenance and water appropriation levels according to institutions that act as a feedback control mechanism (e.g., Cifdaloz et al. 2010). Such feedback controls help farmers to achieve stable crop production levels despite fluctuations in conditions.

Further, a fundamental property of all feedback systems is that designed features that confer robustness to certain kinds of disturbances cause the systems to harbor hidden fragilities to unexposed disturbances (Csete and Doyle 2002). This *robust yet fragile* nature of feedback systems provides an important insight to SES management because patterns of shifting fragilities have been indeed observed in some SES despite human efforts to build robustness (e.g., Anderies 2006, Janssen et al. 2007). The notions of feedback control for robustness and tradeoffs in robustness are not explicitly considered in resilience thinking. Given these differences between robustness and resilience, robustness, though less well known than resilience, is the more fitting conceptual tool with which we can study the dynamics of SES that depend on physical or social infrastructure. Throughout this thesis, I use the concept of robustness more often because the irrigation and forestry systems that I study are partially designed with some physical or social infrastructure to achieve a certain performance objective.

1.3.5. Resilience engineering of built systems

There is also the concept of resilience engineering, which views resilience as "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" (Hollnagel et al. 2011). Inspired by the concept of resilience as developed in ecology and the SES research, safety management engineers and policy makers have recently begun to embrace resilience engineering as a viable approach to complement their existing safety management approach of complex infrastructure systems (Fiksel 2003, Hollnagel et al. 2006). Engineers working with infrastructure systems have traditionally focused on robustness, i.e., how to reduce the sensitivity of a desired system output to a known set of disturbances. To attain robustness, engineers typically use the risk-based engineering approach, which entails identification of all possible threats and their probabilities through risk analysis and implementation appropriate designed fixes to deal with those threats in advance. However, in the face of global change, this kind of approach is insufficient for sustaining infrastructure systems because it is impossible to predict all possible threats (especially the once in one-hundred-year type disturbances) and their probabilities.

This realization has motivated some safety management professionals to consider resilience engineering as a complementary approach to the conventional risk-based engineering. The basic idea is to complement the conventional approach by investing in and improving the general capacity of a system to adapt to changing conditions and to effectively deal with and recover from all kinds of disturbances. Hollnagel (2014) outlines four main abilities that constitute resilience engineering: the ability to respond to various kinds of disturbances (both familiar and unfamiliar ones), the ability to monitor what is going on (e.g., the status of system performance, ecological conditions, and human behavior), the ability to learn from the consequences of past decision-making, and the ability to anticipate and proactively adapt to changing conditions. Although these insights provide only conceptual guidelines, they are useful heuristics with which we can work to enhance SES adaptability. In a nutshell, resilience engineering can be thought of as a form of general resilience heuristics applied to built systems. It is crucial to note that resilience engineering is intended to complement the conventional risk-based approach, not to replace it.

1.3.6. Coalescing robustness and resilience engineering

The two fields of robustness of SES and resilience engineering may be on a path to convergence unknowingly because both concepts in fact argue about similar issues and solutions to deal with the challenge of maintaining SES in the face of change. Safety management professionals, who have traditionally focused on robustness through risk analysis, are now beginning to embrace resilience engineering to improve adaptability to deal with all kinds of disturbances. That is, they are expanding their focus from considering tradeoffs in robustness of infrastructure systems to different disturbances to more a general form of resilience of coupled infrastructure and social systems to deal with irreducible uncertainty. In comparison, the research on robustness of SES has its roots on the opposite side—a group of scholars who have worked with resilience thinking felt that it is conceptually difficult to apply resilience ideas to SES with strong presence of designed components. Further, they felt that resilience thinking does not explicitly address the patterns of tradeoffs in robustness in SES that result from efforts to build robustness to a particular disturbance. As such, they embraced the concept of robustness to better reflect the persistence of and robustness-fragility tradeoffs associated with infrastructure-dependent SES.

However, one must realize that adoption of robustness ideas does not mean rejection of resilience and vice versa. Robustness scholars argue that when the time scale of analysis is in the units of decades or longer, resilience may be a more fitting conceptual tool because it incorporates aspects such as adaptability and transformability that begin to matter in such longer time scales (Anderies et al. 2013b). When the time scale is shorter (i.e., in the units of few years or months) and system boundaries are narrowly-defined (i.e., a small-scale irrigation system), robustness may be more fitting because it explicitly deals with the sensitivity of a well-defined system output to a particular shock and the shifting fragilities that may result from design choices. Hence, resilience and robustness are complementary concepts—the choice between the two concepts ultimately depends on the nature of system boundary, time-scale, and the specificity of output measure that one is considering (ibid).

Robustness scholars also show how robustness and resilience relate to each other through the intermediary role of adaptability (ibid). In a short term, social actors managing a SES can achieve robustness by deciding which disturbances they want to be robust against and which fragilities they can live with at a particular point in time. Robustness better facilitates this process because it forces analysts to consider a precise system boundary and output measure and potential robustness-fragility tradeoffs associated with design choices. In a longer term, adaptability can be used to navigate through robustness-fragility tradeoffs. In response to a changing environment, actors can sense changing conditions and learn to dynamically adapt their system robustness characteristics. That is, by constantly adjusting decisions to achieve short-term robustness at a particular point in time through the exploration of robustness-fragility tradeoffs, social actors may be able to achieve long-term resilience to deal with all kinds of change and uncertainty. Hence, robustness and resilience are closely related concepts and complement each other.

Similarly, resilience engineering does not claim that resilience is a panacea and should replace the conventional risk-based approach. It simply argues that risk analysis alone is insufficient for dealing with uncertainty associated with global change and thus should be complemented by improved adaptability to deal with all kinds of shocks (Park et al. 2013). Hence, one could interpret the four main abilities of resilience engineering (the ability to respond to various kinds of disturbances, the ability to monitor what is going on, the ability to learn from the consequences of past decision-making, and the ability to anticipate and proactively adapt to changing conditions) as system adaptability characteristics that are needed to achieve long-term resilience via short-term robustness built through maneuvering robustness-fragility tradeoffs. In short, both concepts acknowledge robust-yet-fragile nature of SES with designed components. Scholars in both fields also suggest that general resilience-related aspects such as adaptability are needed to cope with hidden fragilities associated with unexposed shocks. Hence, a possible area of future research may be to explore ways in which the concepts of resilience engineering and robustness of SES can be coalesced to create a unified conceptual tool with which engineers, ecologists, and social scientists can work to understand the sustainability of infrastructure-dependent SES.

1.4. Collective action and the self-governance of the commons

Common-pool resources (CPR) are defined by two characteristics: high cost of exclusion and subtractability in use (NRC 1986, Berkes et al. 1989, Feeny et al. 1990). High cost of exclusion means that it is costly or difficult to exclude outsiders or those who do not hold rights from accessing and using the resource. For example, a large forest commons cannot be easily enclosed and monitored 24 hours per day to prevent outsiders from accessing the resource. Likewise, it is difficult to enclose and monitor mobile resources such as migrating stocks of fish. Subtractability in use means that one person's resource consumption leads to less of the resource available to others. An amount of fish, forest resources, and irrigation water appropriated by one user subtracts from what is available to other users.

These two characteristics of CPR open the door to two types of collective action problems: provision and appropriation problems (Ostrom et al. 1994). Provision problem concerns how to motivate users to contribute to a shared infrastructure (e.g., irrigation infrastructure) that makes resources available for appropriation. Overcoming the problem of provision, however, is difficult because of the high cost of exclusion. Users face temptation to free-ride by taking benefits from the shared infrastructure without making contributions to it. Appropriation problem concerns how to curb an individual's excessive resource consumption. Because benefits of one individual's resource consumption accrue solely to that individual while resulting negative effects (e.g., resource degradation) are shared by all others, individuals face temptation to take as much resources as possible while they last.

In the absence of proper incentive mechanisms, self-interested, rational actors will likely act to pursue individual gain and harm group interest when facing the collective action problems (Sally 1995, Kollock 1998). Under-provision of infrastructure (less of positive externality) and excessive consumption of resources (more of negative externality) are probable in such situations. Thus, SES in which CPR are managed will likely be on the path to the tragedy of commons unless institutions are devised to restrain excessive resource appropriation and promote contributions to shared infrastructure (Ostrom 1990).

Creation and enforcement of institutions, however, are difficult in their own right because they entail a second-order provision problem (Kollock 1998, Boyd and Mathew 2007, Ostrom 2008). Creation and enforcement of institutions incur costs on those who supply them as shared social infrastructure, but the resulting benefits are shared by many. If it is difficult for humans to overcome the first-order problems of provision and appropriation of commons, why would they solve the even more difficult problems of creating and enforcing institutions at a cost to themselves? Because of the inherent collective action problems and the prevailing view that humans are self-interested rational actors, the conventional wisdom of natural resource management until the 1980s has been that either state control or privatization of commons is needed to prevent the destruction of natural resources (Poteete et al. 2010). This conventional thinking, however, has been debunked by numerous comparative studies of field cases (NRC 1986, 2002, Wade 1988a, Ostrom 1990, Baland and Plateau 1996), behavioral experiments of commons dilemma (Ostrom et al. 1992, Janssen et al. 2010, 2011a), and mathematical models (Sethi and Somanathan 1996) that demonstrated the capacity of humans to self-organize and overcome the provision and appropriation problems.

Douglas North defines institutions as "humanly devised constraints that shape human interaction", and asserts that the main role of institutions is to "reduce uncertainty by providing a structure to everyday life" (North 1990). Elinor Ostrom refers to institutions as "rules that humans use when interacting within a wide variety of repetitive and structured situations at multiple levels of analysis" (Ostrom 2005a). These characterizations of institutions explain why institutions help humans to overcome collective action problems. Because humans tend to be rational (or boundedly-rational) actors with imperfect information, we often feel uncertain about the future actions of others in collective action situations and expect others to feel the same way (North 1990). Hence, trust is difficult to emerge, and it is costly for humans to transact with others to achieve productive outcomes in collective action situations. The beneficial role of institutions is that they alleviate such a state of uncertainty and lower the cost of transaction by brining structure and order to our everyday interactions with others (ibid). Such a state of structure and order creates an environment conducive for trusting relationships to develop and collective action to follow (Ostrom and Ahn 2003).

However, institutions incur transaction costs on those who supply and enforce them as shared social infrastructure. Transaction costs are defined as costs of exchange or costs of measuring and enforcing contractual agreements (Coase 1937, North 1990, Ménard and Shirley 2008). For example, enforcing a rule on restraining the amount of catch in a fishery may incur substantial monitoring and sanctioning cost to those involved. If the benefits of deploying institutions do not outweigh the transaction costs of doing so, people will not follow and maintain the institutions. Then, from an institutional design perspective, a key challenge to overcoming collective action problems surrounding the commons is how to devise institutions that can promote and sustain collective action without excessive transaction costs.

Through comparative analyses of case studies of commons, a number of scholars identified commonly-occurring features of long-lasted CPR management regimes (Wade 1988a, Ostrom 1990, Baland and Plateau 1996, see Agrawal 2002 for a comparative analysis). Among these, the design principles (DP) of long-lasted institutions developed by Elinor Ostrom (1990) have gained prominence among scholars. These principles include (DP 1) clearly defined user and resource system boundaries, (DP 2) congruence between costs and benefits of using the commons, (DP 3) collective-choice arrangement that allows users to participate in decision-making processes, (DP 4) monitoring by those who are accountable or appropriators themselves, (DP 5) graduated sanction against rule violations, (DP 6) cheap and effective conflict resolution mechanism, (DP 7) recognition of users' legal rights to self-govern their resource system, and (DP 8) nested enterprise in the case of large-scale commons.

DP 1 and 2 address the core challenges of collective action and the commons: free-riding and excessive resource consumption. DP 3 and 7 facilitate users to self-govern the commons and continuously adapt and refine their institutional arrangements in response to changing conditions. These four principles, however, are insufficient on their own to maintain collective action. Additional features such as monitoring and graduated sanction (DP 4 and 5) and conflict-resolution mechanisms (DP 6) are needed to continuously enforce and bolster the governance regime. Taken together, these principles facilitate a set of reinforcing processes that sustain a successful governance regime of SES.

1.5. Robustness of communal irrigation and forestry systems

In this thesis, I use communal irrigation and forestry systems as a testing ground to examine how infrastructure design affects SES robustness. Communal irrigation systems managed by farmers (Yoder 1994) are commonly found in the developing world (e.g., Wade 1988a, Tang 1991, Lam 1998, Dayton-Johnson 1999, Bardhan 2000, Baker 2007). These systems still serve a large portion of total irrigated area in many developing countries, especially those in Asia (Barker, Randolph; Molle 2004). In fact, 90% farms worldwide cultivate less than 2 hectares of land, and most of such small-holder farmers practice irrigated agriculture to produce nearly 40% of global agricultural products (Wallingford 1997, McIntyre et al. 2009). Hence, irrigated agriculture operated by small-holders is paramount to global food security and rural livelihood sustainability.

More importantly for our purposes, farmers in these systems depend heavily on physical infrastructure to produce a crop (Ostrom and Gardner 1993). They bring water to their fields through production infrastructure (e.g., water diversion structure such as dams and weir) and distribution infrastructure (e.g., water conveyance structure such as canals). The presence of this physical infrastructure, however, challenges the robustness of irrigation systems by introducing two types of collective action problems (Ostrom et al. 1994). First, farmers need to mobilize collective labor to repair water diversion structure and clean canals each year. If too many farmers free-ride by skipping collective maintenance activities, the irrigation system will eventually cease to function (threshold public goods dilemma). Second, farmers located along the canals need to coordinate among themselves to achieve fair distribution of water. But achieving fair water distribution is difficult because the physical layout of canals often leads to upstream-downstream asymmetry among farmers. That is, farmers located in upstream locations access water before those in downstream locations, and consequently face temptation to take more water than others (asymmetric commons dilemma). This heterogeneity makes the system fragile to economic inequality—unless the opportunistic behavior of upstream farmers is checked, downstream farmers are most likely left with little or no water during water-stressed cropping seasons. In such situations, collective action will likely fail because downstream farmers who do not get enough water often retaliate by reducing contributions to infrastructure maintenance (Janssen et al. 2011b).

The robustness of communal irrigation systems is also affected by new livelihood opportunities, as rural communities become increasingly integrated into wider socioeconomic fabric (e.g., Baker 1997, Araral 2013). New livelihood opportunities may affect at least two situational variables that influence whether groups self-organize to overcome collective action problems: user dependence on resource and the option to enter or exit from a group (exit option) depending on whether users are dissatisfied with outcomes (Basurto and Ostrom 2009, Poteete et al. 2010). With growing economic globalization, social norm for collective action will likely be eroded as younger generations leave for better-paying wage labor opportunities in urban areas.

Further, there is growing evidence that communal irrigation systems will likely face water-related stresses from changing climatic patterns (Arnell 1999, Tubiello et al. 2007, Immerzeel et al. 2010). For example, in some arid regions, farmers may face reduced precipitation in early stages of cropping season because of climate change, but the predicted rainfall during the summer monsoon season is expected to increase (IPCC 2007). Such changing patterns in water availability may pose significant challenges to the capacity of existing physical and social infrastructures of an irrigation system that have been optimized to past conditions.

Community forestry has supported the livelihoods of countless rural populations worldwide (WRI 2003). Many rural households depend on forests for securing resources such as firewood, fodder, and timber (Dorji et al. 2003, Andersson and Agrawal 2011). In these resource systems, a social unit (a village) sometimes forms a federation or links with other social units (neighboring villages) to co-manage a shared forest commons. The resulting organizational form or structure—a prime example of which is nested enterprise—is a kind of social infrastructure that humans develop to efficiently manage large-scale commons (Ostrom 1990).

Nested enterprises, defined as having multiple centers and layers of management, are built on the structure of horizontal and vertical social links (Andersson and Ostrom 2008, Mwangi and Wardell 2012). Horizontal links can be thought of as inter-community connections (e.g., shared property rights or joint collective action) through which management tasks and appropriation activities are coordinated. Vertical links, on the other hand, are connections between different levels of social organization. Together, these social links are known to contribute to adaptive capacity of SES in several ways. Nested enterprises allow oversight and tasks to be assigned at levels of organization that better reflect local conditions. The division and layering of duties also help to economize the transaction costs of managing a SES (especially in cases of large-scale commons).

But the cost of maintaining such a social infrastructure is not zero—it takes time and the efforts of participating social units to regularly interact to coordinate their activities, resolve conflicts, and to assess trustworthiness of each other. In order for this type of social infrastructure to persist over time, the benefit of maintaining social links for nested enterprise must outweigh the costs of doing so. An interesting question is: how will the design of this type of social infrastructure affect the robustness of self-governed forest commons under economic globalization? For example, what happens if there is influx of substitute goods for forest resources (e.g., coal and oil) that can significantly lower the economic salience of maintaining forest commons? The design of existing horizontal and vertical social links may influence how the systems adapt or reorganize under such novel conditions.

2. THE EFFECT OF PHYSICAL INFRASTRUCTURE ON THE DYNAMICS OF SOCIAL-ECOLOGICAL SYSTEM

2.1. Introduction

Human societies now find themselves embedded in a myriad of social-ecological systems (SES) that depend heavily on the physical infrastructure. How physical infrastructure mediates human-environment interactions is thus the linchpin of many pressing sustainability challenges in contemporary SES (Anderies et al. 2004). For example, the resilience of urban systems to natural hazards often depends on engineered structures such as levees, roads, or buildings. Similarly, global food security depends on irrigation infrastructure through which farmers obtain water. In mediated SES, the presence and particularly the *design* of physical infrastructure fundamentally shape the dynamics of coupled social and natural processes (Park et al. 2013, Anderies 2014a, Linkov et al. 2014).

A major puzzle for sustainability in this era of global change rests on a deep understanding of interactions among social, natural, and physical components and the effects of such interactions on the robustness of SES to unexpected disturbances. **How can the design of physical infrastructure affect the capacity of SES to maintain vital functions in the face of disturbances? What are design criteria for physical infrastructure for more robust SES?** This chapter examines these questions using a simple formal model of a community irrigation system—a classic case of a SES in which physical infrastructure is the key interface between social and ecological processes.

Communal (or farmer-managed) irrigation systems (Yoder 1994) are widespread in rural areas of the developing world (Wade 1988a, Tang 1991, Lam 1998, Bardhan 2000, Trawick 2001, Baker 2007), and even today serve a significant portion of the total irrigated area, especially in Asia (Barker, Randolph; Molle 2004). These systems provide an excellent testing ground for exploring how infrastructure affects SES. Farmers need a reliable supply of water to produce food and often move water from its source through production infrastructure (weir) and distribution infrastructure (canals). Two strong empirical regularities emerge from a long-term comparative case analysis of robustness of such systems. The first regularity is regarding the critical importance of infrastructure maintenance and the collective action or cost-sharing problems associated with it (Ostrom and Gardner 1993, Dayton-Johnson 2003). For instance, a study of 50 irrigation systems in Nepal found that farmer-managed systems have cruder infrastructure than agency-managed systems in the form of temporary headworks and unlined canals (Bastakoti and Shivakoti 2011). This kind of infrastructure demands greater mobilization of collective labor or investment each year to maintain functionality (a threshold public good dilemma). The second empirical regularity is regarding the challenge of achieving fair water distribution, which can be undermined by upstream-downstream asymmetry stemming from the canal layout (an asymmetric commons dilemma) (Ostrom and Gardner 1993, Bardhan and Dayton-Johnson 2002). Because of the tight links between livelihoods, social dilemmas, resource flow, and infrastructure, it has been suggested that community irrigation systems are to the study of SES sustainability what fruit-flies are to the study of evolutionary biology (NRC 2002, Janssen and Anderies 2013).

Irrigation infrastructure, which is key to meeting food security—especially in South Asia where most of the poor people reside—is in dire need for maintenance. Much of this infrastructure, built in the 1960s and 1970s, has deteriorated rapidly and poses a major threat to food security in the region (Huppert et al. 2003). Lack of funding is generally given as the reason behind the deterioration. While this is certainly important, this chapter focus on the collective action problem that maintenance poses in farmer-managed systems by characterizing the structure of incentives that users face under different design conditions and tracing the dynamics that follow. Our focus on the interactions between the infrastructure design and the incentives facing user groups is novel and opens doors to alternative ways of thinking about solutions to the maintenance problem, beyond the budgetary considerations. This problem is highly relevant to current discussions on global food security. Nearly 90% of farms worldwide are operated by small-holder farmers who cultivate less than 2 hectares of land (McIntyre et al. 2009). Most of these small-holders practice irrigated agriculture, which consumes roughly 70% of global developed water supplies and produces nearly 40% of global agricultural output (Wallingford 1997). It is imperative to understand how these small-holders can continue to maintain cooperation and, with it, critical infrastructure in the face of a globalized and rapidly changing world.

I address the question of how infrastructure design affects SES sustainability in two stages. First, I explore the effects of different design conditions on long-term system behavior in our model system. I examine two types of distribution infrastructure, one with and one without upstream-downstream asymmetry, and different thresholds of infrastructure maintenance. Second, I evaluate how these design conditions influence the robustness of system function to an economic shock. Our model results suggest that how infrastructure is constructed can cause regime shifts, i.e., fundamental changes in qualitative system behavior. Regimes of sustainability, persistence with economic inequality, and system collapse emerged, expanded, or shrunk as I varied the designed features in the model system. I also observed that infrastructure design can influence the robustness (or sensitivity) of system performance to socio-economic shocks such as an increase in the attractiveness of alternative livelihood opportunities. It is important to note, however, that our goal is not to accurately model the dynamics of a particular irrigation system. Rather, the goal of studying the stylized model is to better understand the mechanisms that may underlie empirical regularities observed in field and behavioral studies, and to explore long-term system dynamics under different design conditions.

What emerges from our analysis is the need to re-conceptualize SES as coupled infrastructure systems (CIS) in which the role of shared infrastructure is clearly present. As suggested by Anderies (2014a), this can be achieved by conceptualizing ecologies of SES more broadly to include both built and natural elements, as in industrial ecology (Graedel and Allenby 2010). This broader view, which will likely be built on earlier conceptualizations of the role of hard infrastructure (Clark et al. 1979) and soft infrastructure in SES governance (Dietz et al. 2003), would help us consider the links among social, natural, and built elements more explicitly. Given the prominence of hard infrastructure in contemporary SES, this broader view better facilitates addressing global challenges to SES sustainability.

2.2. The nature of irrigation system

In general, irrigation systems both increase crop production (by enabling an increase in cropping intensity) and stabilize yields despite variability in annual water supply. To obtain these benefits, farmers must maintain shared infrastructure, and create and enforce governing rules to coordinate the infrastructure-maintenance and water-distribution processes (Dayton-Johnson 2003). These conditions typically occur in farmer-managed irrigation systems in several developing country contexts. Without effective rules for allocation, monitoring, and enforcement, farmers can free-ride by taking irrigated water without contributing labor or fee to the maintenance work. Likewise, upstream farmers can use their location advantage to over-appropriate water, leaving an unfair share of water for downstream users during the distribution process (Bardhan and Dayton-Johnson 2002). Interestingly, these two processes often become interdependent because maintenance of infrastructure often requires a critical mass of labor, i.e., upstream farmers usually cannot carry out the task without help from downstream farmers (Ostrom and Gardner 1993, Lam 1996). This interdependency likely affects the likelihood that upstream farmers will over-appropriate water because downstream farmers who do not get enough water can retaliate by reducing their inputs to maintaining infrastructure (ibid).

Despite the many challenges facing farmers, field studies have identified several irrigation communities that have successfully maintained their infrastructure and achieved fair water distribution for hundreds of years (Bacdayan 1974, Siy 1980, Wade 1988a, Gupta and Tiwari 2002, Baker 2007). These long-lived systems typically have well-tuned rules to govern user behavior (Ostrom 1990). Behavioral experiments have followed up on field-study findings by demonstrating that individuals in small groups (say, 5 players) can endogenously solve relatively complex commons dilemmas associated with irrigation if allowed to communicate (Janssen et al. 2011b). These studies suggest that players were willing to tolerate some inequality in the amount of appropriated water, as long as there was some proportional equivalence between investments in and benefits from shared infrastructure (ibid). However, this tolerance declined with external shocks, i.e., inequality may make systems more sensitive to variability (Anderies et al. 2013a).

Recent studies stress that contextual variables, such as attributes of physical infrastructure, the availability of exit options, or power asymmetries, influence human decisions in SES collective-action situations (Agrawal 2002, Bardhan and Dayton-Johnson 2002, Poteete et al. 2010). A related question that this chapter addresses is how these factors combine to affect SES robustness. Here, I use modeling to help answer these questions. Specifically, how do maintenance thresholds and asymmetric access interact to influence collective action outcomes and robustness in the long run?

2.3. The basic model structure

Suppose that N farming households are spread across two villages (Village 1 and Village 2) that manage a shared irrigation infrastructure. The number of households in each village is N_1 and N_2, respectively, which satisfy $N_1 + N_2 = N$. Each farmer is endowed with the same amount of available labor (l) each year and the same acreage (a). A farmer may appropriate a volume of water (q) from the system, and allocate labor among three kinds of work: farming (l_f), maintaining infrastructure (l_m), and outside employment (l_e) with wage rate w, i.e., $l = l_f + l_m + l_e$. Then, a farmer's income is $\pi = pf(l_f, q, a) + wl_e$, where $f(l_f, q, a)$ is the production function for agricultural yield, p is the price per unit of agricultural yield, and wl_e is the employment income. Similarly, the aggregate income of the two villages is given by $\Pi = pF(L_f, Q, A) + wL_e$ (upper case symbols represent aggregate-level quantities).

To receive irrigation water, farmers have to maintain the physical infrastructure each year (canals must be cleaned of silt and debris, and water diversion structures such as weirs must be repaired). If farmers' aggregate maintenance labor (L_m) exceeds the threshold of maintenance, the infrastructure can continue to deliver water. If too few farmers contribute labor, the infrastructure delivers no water. This threshold of maintenance is a design parameter that varies across different irrigation systems depending on physical characteristics of the irrigation infrastructure. For example, if a weir is located in the shallow reaches of a river where the cross-section is wide, there is greater accumulation of silt and thus greater need for maintenance (Baban 1995). I use a piece-wise linear function $I(L_m)$ (Figure 2.1 A) to represent this threshold. The parameter

ψ is the half-saturation point of L_m, yielding half of the maximum infrastructure efficiency ($I_{\max}$). The parameter ϵ controls the slope of the threshold. It follows that the threshold of maintenance is $\psi - \epsilon$. Total irrigation water is given by $Q = I(L_m)S(t)$, where $S(t)$ is the state of a renewable water resources system such as river. In this study, $S(t)$ is assumed to be constant ($S(t) = S$).

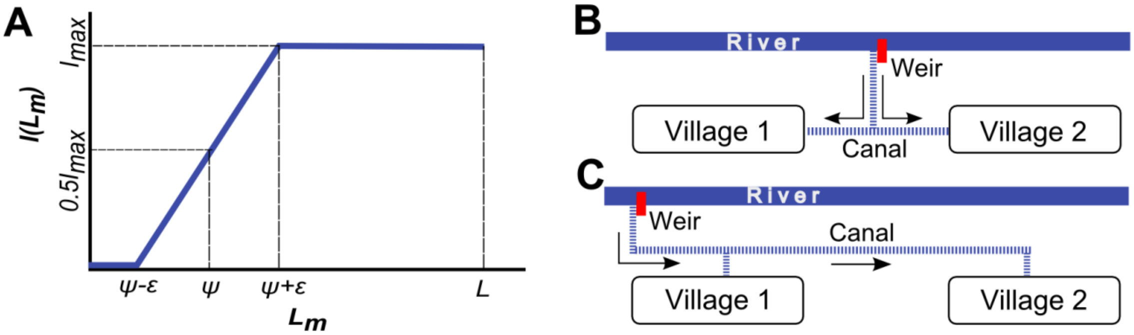

Figure 2.1. Designed aspects of the irrigation infrastructure. Panel A shows the efficiency of irrigation infrastructure $I(L_m)$ as a function of maintenance labor L_m. The half-saturation point of labor (ψ) and half-width of the threshold slope (ϵ) determine the threshold of maintenance ($\psi - \epsilon$). When $\epsilon = 0$, slope is infinite and no water is generated until $L_m = \psi$. When $\epsilon = \psi$, the amount of water increases linearly with L_m until $L_m = \psi + \epsilon$. Panels B and C show two types of distribution infrastructure. In B, two villages have equal access to water. In C, Village 1 has advantage over Village 2 in water access.

Our model system is governed by the following rules. Maintenance labor to be contributed by a farmer is proportional to his or her acreage (Dayton-Johnson 2003), which is assumed to be the same for all farmers in this study. Water allocated to a farmer is proportional to his or her acreage, but only among the water rights holders—only farmers who contributed labor to the infrastructure prior to the planting season obtain water rights. Reflecting on Ostrom's institutional design principles for long-lived commons (Ostrom 1990), these rules ensure that the benefits and costs borne by a farmer are proportionate to each other.

Farmers choose between two strategies: group-conformist (*G*) and opportunist (*O*). The model tracks the fraction of *G*s in Village i denoted by $X_i = N_i^G / N_i$. I define the total number of *G*s as $N^G = N_1^G + N_2^G$. Accordingly, the fraction of *O*s in Village i is $1 - X_i = N_i^O / N_i$ (I use the notational convention that subscripts and superscripts refer to village and agent type, respectively, on all variables throughout the remainder of the paper). *G*s follow and enforce the rules, and strive to maximize the total welfare of the two villages. Each *G* assumes everyone will contribute to the shared infrastructure and contributes their proportionate share ($1/N$) of the socially optimal maintenance labor (L_m^*), attempts to take only the allocated share ($1/N^G$) of the total irrigated water (Q), and allocates labor between farming and employment to maximize the total income. L_m^* is the maintenance labor that would maximize the total welfare of the two villages via optimal production of Q, as would be prescribed by a village leader acting as a benevolent social planner. Further, *G*s monitor for rule violations in their own Village i and the other Village j ($i \neq j$), and punish violators at a cost to themselves (see Ostrom 1990, Ostrom et al. 1992, Fehr and Gächter 2000 for related examples). The cost of enforcement for a *G* increases with the frequencies of *O*s (Sethi and Somanathan 1996) , i.e., $\left[\gamma_s\left(1 - X_i\right) + \gamma_o\left(1 - X_{\bar{i}}\right)\right]$ where γ_s and γ_o represent the maximum enforcement costs for the same village and the other village, respectively. Note that $\gamma_o > \gamma_s$ because it is probably easier to enforce the rules within a same village.

*O*s, in contrast to *G*s, break the rules and attempt to maximize individual net income. They contribute zero maintenance labor, and thus do not hold water rights. Nevertheless, they take as much of other farmers' water as they can within the limits set by the penalties imposed, their capacity to compete for water relative to others, and the benefits to be gained from the outside employment. *O*s take an amount of water and allocate labor to employment to maximize individual net income. The probability of being caught and punished increases with N^G, i.e., $(X_1 + X_2)/2$. The penalty varies by situation: it increases with the amount of water stolen (q^O; i.e., graduated sanction), but decreases with water abundance in the system. When water is abundant, rule violations are tolerated because farmers have little incentives to concern themselves with equity issues (Adams et al. 1997). Empirical evidences show that resource users would be less likely to self-organize when resource is abundant (Agrawal 2002). This effect is represented by $\delta[1 - \sigma Q(L_m)/Q(L_m^*)]q^O$; where δ is the maximum penalty, $Q(L_m)/Q(L_m^*)$ is the proxy for water abundance, and $\sigma \le 1$ is the tolerance factor.

In summary, the payoffs for *G* and *O* in Village i are expressed as the following:

$$\pi_i^G = pf(l_f^G, q_i^G, a) + wl_e^G - \gamma_s(1 - X_i) - \gamma_o(1 - X_j)$$
$$\pi_i^O = pf(l_f^O, q_i^O, a) + wl_e^O - \delta\left(1 - \sigma\frac{Q(L_m)}{Q(L_m^*)}\right)q^O\left(\frac{X_i + X_j}{2}\right)$$

where j denotes the other village ($i \ne j$). See APPENDIX A for more details on the equations. Finally, replicator equations (Taylor and Jonker 1978) were used to model the dynamics of the two strategies within each village (Sethi and Somanathan 1996). The changes in the fraction of *G*s (X_i) in Village i is given by:

$$dX_i / dt = X_i[\pi_i^G - \bar{\pi}_i]$$

where $\bar{\pi}_i$ is the average payoff of a farmer in Village i, i.e., $\bar{\pi}_i = \pi_i^G X_i + \pi_i^O(1 - X_i)$. Our results were obtained from numerical simulation of the above system of equations.

2.4. Infrastructure design

The parameters ψ and ϵ (Figure 2.1 A) together represent the maintenance threshold of the irrigation infrastructure. The threshold could be high and sharp (small ϵ, $\psi - \epsilon \approx \psi$) or low and gentle in slope ($\psi - \epsilon \approx 0$). The former case would fit a system characterized by a distant large-scale production structure coupled with long distribution networks. Examples of this can be found, for instance, in the major irrigation systems found in the plain regions of India (Wade 1988a). A scalable system with small-scale production units and shorter distribution networks would be approximated the latter case. Examples of this can be found in the hilly terrains of Nepal (Bastakoti and Shivakoti 2011) and Taiwan and South Korea (Wade 1988b).

Another infrastructure feature is upstream-downstream asymmetry. When upstream-downstream asymmetry is absent (Figure 2.1 B), we essentially have a symmetric common-pool resource (CPR) situation in which two villages have an equal access to a shared commons (for simplicity, let us assume that *within* each village, farmers have equal access to water). This happens in what is referred to as 'bifurcated' layout of canals in irrigation engineering literature, and is observed in several traditional irrigation systems (Horst 1998). Several modeling studies have examined SES dynamics in such a CPR situation (Ito 2012, Tavoni et al. 2012, Lade et al. 2013). In this setting, farmers are symmetric in their capacity for competing for water because they all have equal access to water and are endowed with the same levels of available labor, technology, and skills[1]. It follows that if all farmers are to rush and compete for water, *O*s will face, on average, the same constraint on the amount of water they obtain ($\leq Q / N$).

When upstream-downstream asymmetry is present (Figure 2.1 C), which is the likely scenario in most irrigation systems, water is accessed sequentially—farmers in Village 1 access water before those in Village 2. This is referred to generally as 'hierarchical' layout design in irrigation engineering literature. Because of their privileged access, users in Village 1 are less constrained on the amount of water they can appropriate than the symmetric case. In this setting, *O*s in upstream face a higher (i.e., less constrained) upper-bound on the amount of water they obtain ($\leq Q / N_1$) (see APPENDIX A for more details). This chapter tested different scenarios of maintenance threshold and asymmetry in distribution to understand how infrastructure design affects qualitative system behavior and robustness characteristics in the long-run.

2.5. Effects of asymmetry

Figure 2.2 A is a phase-space representations of the overall cooperation level of the system with asymmetry. Three regimes are possible: *ALL-O*s; a sustainable situation

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[1] Of course, this assumption is restrictive because farmers would likely be heterogeneous in their acreage in most irrigation systems. Nevertheless, this assumption enables us to focus on the effects of asymmetry in distribution infrastructure.

in which most are *G*s in Village 1, but all are *G*s in village 2 (*MOSTLY-G*s); and a decoupled situation in which the two villages stop collaborating for a common goal, i.e., *G*s dominate in Village 1 but *O*s prevail in Village 2 (*DECOUPLED*). In the absence of asymmetry, two regimes typically emerge for most parameters explored: all *O*s ($X_1 = 0$ and $X_2 = 0$) and all *G*s ($X_1 = 1$ and $X_2 = 1$). There is no inequality in total income between Villages 1 and 2 in these two regimes (see APPENDIX A for the details on the effects of symmetry).

Figure 2.2 B compares the performance of the three regimes of the asymmetric case: the levels of infrastructure efficiency and inequality in total income. At *ALL-O*s, no water is supplied and everyone is equally bad off. At *MOSTLY-G*s, water is almost fully supplied and the two villages have a roughly equal total income (but the income of Village 1 is somewhat higher than that of Village 2). At *DECOUPLED*, some water is supplied but considerable income inequality exists at village-level because only farmers in Village 1 obtain irrigated water. Farmers in Village 2 leave agriculture and resort to outside employment.

Let us now take a closer look at the *MOSTLY-G*s and *DECOUPLED* regimes in the asymmetric case. The total income of Village 1 is higher than that of Village 2 in both regimes (but the inequality is much more severe in *DECOUPLED*). This is consistent with existing knowledge of irrigation systems (Ostrom and Gardner 1993, Baker 2007, Janssen et al. 2011b). At *MOSTLY-G*s, some *O*s exist in Village 1, but all are *G*s in village 2. This slightly unfair regime occurs because *O*s in Village 1 are less constrained in the amount of water they appropriate than *O*s in Village 2. This advantage enables some *O*s to survive in Village 1 in the asymmetric case. The system converges to

DECOUPLED when enough *G*s exist in Village 1 but few *G*s exist in Village 2 at the outset. Because water rights holders (*G*s) are few in Village 2, *G*s in Village 1 pass down little water, which becomes subject to fierce competition between many *O*s and few *G*s in Village 2. Because of this competition for scant water, the amount of water that downstream *O*s get is decided by the physical limit of available water rather than by the penalty they face. It follows, then, that *G*s and *O*s in Village 2 end up obtaining an equal amount of water. Eventually, *O*s prevail in Village 2 because they are penalized little (because they obtain only a meager amount of water), appropriate the same amount of water as *G*s', and free-ride on maintenance labor. In contrast to Village 2, *G*s win over *O*s in Village 1—a substantial amount of water is available in upstream and *G*s obtain more water than *O*s by means of enforcement. Hence, the system converges to *MOSTLY-G*s in the long-run.

It is important to note that *MOSTLY-G*s and *DECOUPLED* are resilient: the system is sustained even though income inequality lingers on. Our findings are concordant with empirical studies. Behavioral experiments have shown that players in irrigation dilemma games may be willing to tolerate some degree of inequality, as long as there is some proportional equivalence between investments in and benefits from infrastructure (i.e., *MOSTLY-G*s) (Janssen et al. 2011b). Field studies also observed that downstream farmers may exit from co-managing a system if there is too much income inequality (i.e., *DECOUPLED*) (Baker 2007).

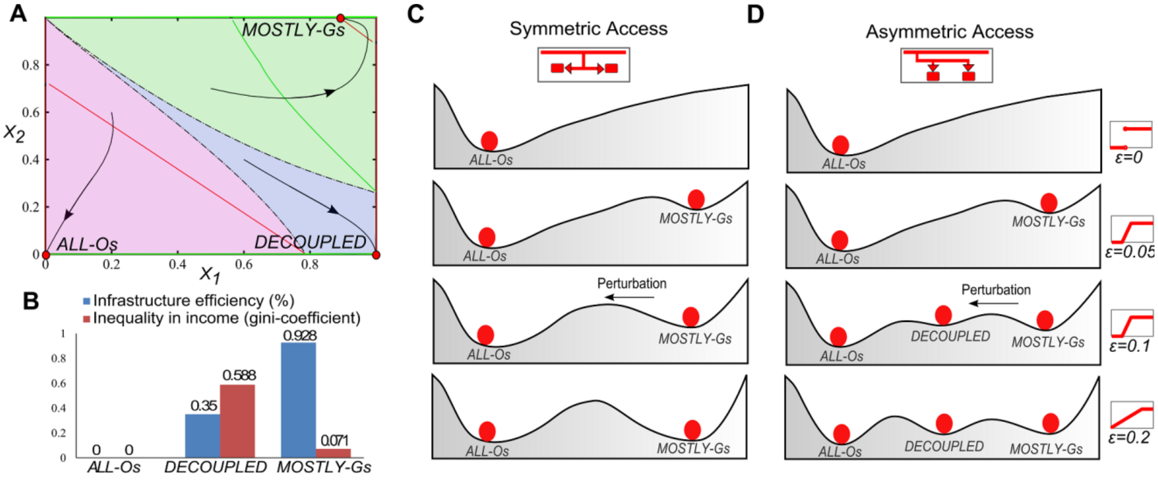

Figure 2.2. Effects of asymmetry and threshold. In Panel A, the *x* and *y* axes show the fractions of *G*s in Village 1 (X_1) and Village 2 (X_2), respectively. Red dots represent stable equilibrium points of the dynamics. Arrows represent the flows of dynamics from particular initial states. Red and green lines represent X_1 and X_2 nullclines, respectively. Panel A shows possible regimes under asymmetry: *ALL-O*s (light pink area), *MOSTLY-G*s (light green area), and *DECOUPLED* (light blue area). At *ALL-O*s, the irrigation system collapses. At *MOSTLY-G*s, most farmers follow the rules, water is almost fully supplied, and some income inequality exists between the villages. At *DECOUPLED* farmers in Village 2 leave farming, and considerable inequality in total income exists between Villages 1 and 2. Panel B shows a comparison of the three regimes shown in A (model with asymmetry) in terms of infrastructure efficiency and income inequality (gini-coefficient) between Villages 1 and 2. Panels C and D show effects of infrastructure design on stability landscape. In Panel C, distribution infrastructure is symmetric and threshold of maintenance is varied from $\epsilon = 0$ to $\epsilon = 0.2$. The small inset graphs in the far right show the shape of the infrastructure-labor relation for each value of ϵ. In Panel D, distribution infrastructure is asymmetric and threshold of maintenance is varied across the same range. (see APPENDIX A for the parameters used).

2.6. Effects of maintenance threshold

Some systems depend on a distant large-scale infrastructure that likely brings no water until some critical amount of maintenance work is done each year. In contrast, a scalable system in which a collection of small-scale infrastructure provides services may start to bring water at much smaller maintenance inputs. Here, we explored how the degree of maintenance threshold affects system behavior in our model system. Figure 2.2 D shows that the threshold can induce regime shifts in the asymmetric system. As the threshold gets lower and gentler in slope (ϵ approaches ψ), *ALL-O*s loses resilience, i.e., its basin of attraction shrinks. At the same time, *MOSTLY-G*s emerges and expands. But this regime shift occurs at the cost of emergence of the *DECOUPLED* regime. The opposite is true when the threshold gets higher and sharper in slope (ϵ approaches zero). These results suggest that low-threshold scalable systems (i.e., $\epsilon \approx \psi$) are less likely to collapse, but are more prone to economic inequality. Conversely, large-scale systems (i.e., $\epsilon \approx 0$) are less likely to have inequality issues, but are more prone to collapse. In the symmetric system, only two regimes are possible: *MOSTLY-G*s and *DECOUPLED* (Figure 2.2 C).

When the threshold is high and sharp (small ϵ), little or no water is generated until most of the population is comprised of *G*s. In such a situation, *DECOUPLED* cannot be stable because upstream farmers alone cannot maintain the infrastructure, i.e., strong interdependency exists between Villages 1 and 2. When the threshold is extremely sharp, *MOSTLY-G*s also becomes unstable because it is too vulnerable to opportunism. The path toward sustainability is much narrower in high-threshold systems because most farmers need to participate in collective action each year just to make the system work. In contrast, when the threshold is low and gentle in slope ($\psi - \epsilon \approx 0$), water supply starts to increase almost linearly even at small labor inputs. Hence, *ALL-O*s has smaller resilience—as soon as some *G*s are introduced, it is better for some farmers to cooperate and get some water than to quit farming (unless, of course, outside wage rates are sufficiently high). However, this departure from *ALL-O*s is accompanied by a higher likelihood of inequality in the system because of the emergence of the *DECOUPLED* regime. At *MOSTLY-G*s, downstream farmers continue to cooperate despite some inequality because the infrastructure generates substantial benefits that trickle down to them. At *DECOUPLED*, however, the system functions poorly with considerable income inequality. Because low thresholds weaken the upstream-downstream interdependency, upstream farmers cooperate only among themselves to obtain enough water (i.e., they do not need labor inputs from downstream farmers).

2.7. Robustness of system performance to shocks

This chapter also explored how the combined factors of maintenance threshold and asymmetry affect the *robustness* of SES in this era of globalization. Field studies have found that, as globalization proceeds, rural communities tend to depend more on nonfarm work; suffer shortage of labor for maintaining shared infrastructure; and experience erosion of social norm for collective action, especially among younger generations (Adams et al. 1997, Baker 2007). Hence, I introduced into our model system a sudden rise in wage rates (Figure 2.3 A) to mimic the pressures of globalization processes. Four types of wage shocks were applied by varying their duration (short and long) and intensity (low and high).

I exposed the *MOSTLY-G*s regime to the shocks under two different infrastructure designs: one with and one without maintenance threshold (both combined with asymmetry). Figure 2.3 B and C show the sensitivity of infrastructure efficiency to the short and long wage shocks, respectively. It turns out that the low-threshold system ($\epsilon = 0.2$) is more sensitive (less robust) to the shocks than is the one with higher threshold ($\epsilon = 0.1$). The reason is that upstream *O*s are more advantaged under low-threshold infrastructure because of the weakened upstream-downstream interdependency. In such a situation, sharp increase in wage rates can cause *O*s to surge in upstream because they still access water while earning extra income from skipping maintenance work. As a result, downstream *G*s progressively get less water despite their maintenance work and thus decline in number gradually. At some point, a limit is crossed—downstream *G*s give up and begin to decline rapidly (the trajectory starting from Point a in Figure 2.3 D). Hence, in the absence of threshold, the infrastructure efficiency of the *MOSTLY-G*s regime is highly sensitive to the economic shocks. The system with higher threshold ($\epsilon = 0.1$) is less sensitive to the economic shocks. This reduced sensitivity stems from the tight upstream-downstream interdependency associated with the maintenance work (i.e., upstream users need labor inputs from downstream users to obtain sufficient water). Upstream *O*s surge initially in response to the wage shocks, but the resulting decline of downstream *G*s feeds back to balance the rise of *O*s in upstream (the trajectory starting from Point b in Figure 2.3 D). Hence, the *MOSTLY-G*s regime can better withstand wage shocks when higher thresholds exist.

I also exposed the *DECOUPLED* regime (i.e., a sustained but highly unequal state) to the shocks under the same design variations. Figure 2.3 E and F show the sensitivity of infrastructure efficiency to the short and long wage shocks, respectively. A different pattern is observed in the *DECOUPLED* regime: the system with a higher threshold

($\epsilon = 0.1$) is more sensitive to the shocks than is the one with a lower threshold ($\epsilon = 0.2$). The reason is that high-threshold systems have lower infrastructure efficiency at the *DECOUPLED* equilibrium. That is, upstream users alone toil to maintain the infrastructure, but obtain only a meager amount of water because of the tight upstream-downstream interdependency. Hence, upstream users react more sensitively to rises in wage rate. Low-threshold systems ($\epsilon = 0.2$) at *DECOUPLED* are less sensitive to the wage shocks because infrastructure efficiency is higher at the *DECOUPLED* equilibrium. In sum, infrastructure design (different degrees of maintenance threshold) can significantly affect the robustness of infrastructure efficiency to wage shocks in our model system. We observed that the *MOSTLY-G*s regime with maintenance threshold ($\epsilon = 0.1$) is less sensitive to the shocks because of the tight upstream-downstream interdependency. But, the same design was associated with more sensitivity in the *DECOUPLED* regime. These results suggest that design or technological fixes to SES must consider the potential for regime shifts and altered robustness characteristics.

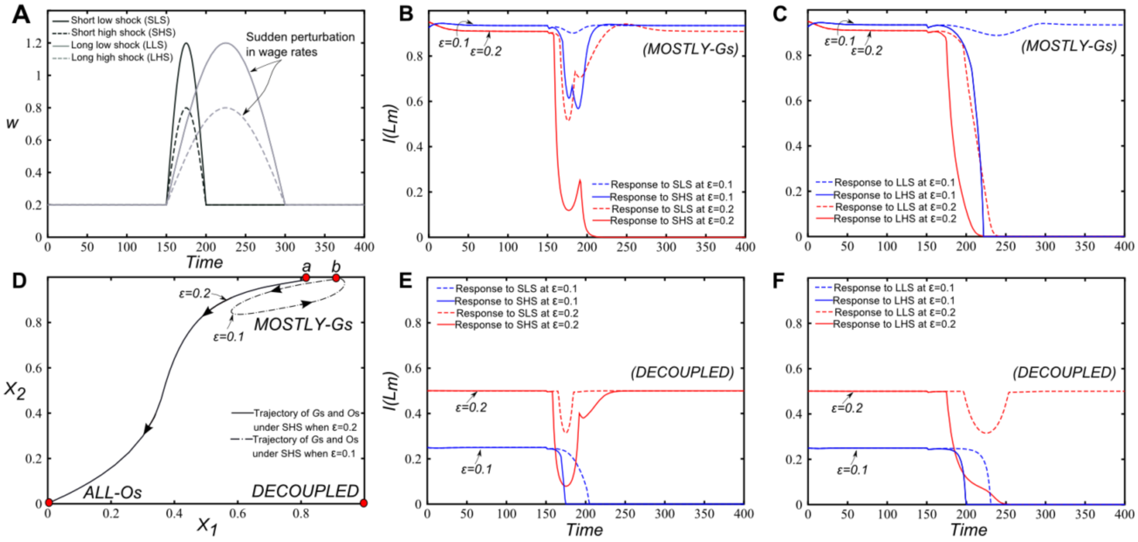

Figure 2.3. Robustness of system performance to wage shocks. Panel A shows profiles of four wage shocks (*w*). Black solid line represents a high shock (HS) in which *w* jumps from 0.2 to 1.2. Black dashed line represents a low shock (LS) in which *w* jumps from 0.2 to 0.8. These shocks apply between $T = 150$ and $T = 200$. Grey lines represent the same shocks applied over a longer duration (between $T = 150$ and $T = 300$). Along with the shocks, we perturb the fractions of X_1 and X_2 a bit at $T = 151$ to observe local stability properties. Panels B and C show the sensitivity of the infrastructure efficiency ($I(L_m)$) at *MOSTLY-G*s to the short and long wage shocks, respectively. Red and blue lines represent the system response when $\epsilon = 0.2$ and $\epsilon = 0.1$, respectively. Panel D shows the trajectories of X_1 and X_2 at *MOSTLY-G*s when the short-duration high shock is applied. Two design scenarios are compared: $\epsilon = 0.2$ (Point a) and $\epsilon = 0.1$ (Point b). Panels E and F show the sensitivity of $I(L_m)$ at *DECOUPLED* to the short and long wage shocks, respectively. Except for the focal parameters, the same default parameter values were used as in Figure 2.2.

2.8. Conclusion

Farmer-managed irrigation systems contain all the basic features of complex SES: hard human-made infrastructure (water diversion and conveyance structures), soft human-made infrastructure (institutional arrangements and organizational forms), and natural infrastructure (watersheds and agricultural land). Understanding how these infrastructures interact and respond to change is critical for maintaining food security for billions of people in the coming decades. Using a model of an irrigation system as a testing ground, I have shown that infrastructure design can greatly influence SES sustainability. When distribution infrastructure exhibits asymmetric access, three regimes can emerge: sustainable, sustained but unequal, and collapsed. We also observed that regime shifts involving these three regimes occur as the maintenance threshold is varied. With a low-threshold scalable infrastructure, the likelihood of system collapse is low. The tradeoff is a higher likelihood that economic inequality will increase. With a high-threshold infrastructure, SES can attenuate the possibility of economic inequality, but the tradeoff is that they become more prone to system collapse. The maintenance threshold also influences the robustness of SES to wage shocks. Under low thresholds, the *MOSTLY-G*s regime is more sensitive to wage shocks. However, the opposite pattern was observed with the *DECOUPLED* regime—high thresholds make the system more sensitive to wage shocks.

Although the purpose of this chapter has been to use this model to illustrate the dynamics of SES, rather than predict behavior, it is worth noting that our model results resonate with some notable cases of irrigation systems in the literature. For example, the community irrigation systems in hilly regions of Nepal, as described by (Bastakoti and Shivakoti 2011), come close to the characterization of a system with low threshold in a *MOSTLY-G*s regime. These kinds of systems have been found to be highly sensitive to wage shocks in recent decades (Ostrom et al. 2011). In contrast, irrigation systems in plain regions of South India, for instance, the Kurnool Cuddapah canal system studied by Wade (1988a) is an example of a *DECOUPLED* system with high thresholds. This system has also been highly sensitive to wage shocks as described by Wade (1988a), and in accordance with our model results. Interestingly though, some specific villages under this system that Wade (1988a) observed to have been successful in developing local collective institutions, fall under a *MOSTLY-G*s regime with high threshold levels. A recent study (Ratna and Reddy 2002) looking at the long term dynamics of the villages with collective institutions found them to be remarkably robust to wage shocks, again as found in our model.

The findings also have some policy relevance. Policymakers must balance the increased robustness of maintaining cooperation and system function that scalable infrastructure (higher ϵ) confers with increased fragility to emerging inequality. Likewise, if biophysical conditions favor large-scale infrastructure (low ϵ), policymakers must be aware of the increased propensity for system collapse and reduced incentives for opportunism. The results also suggest the need for anticipatory approach—institutional considerations should not follow as derivatives from infrastructure after it has been built but as factors that should enter as part of project design itself to enhance robustness.

These outcomes highlight the need to re-conceptualize SES as coupled infrastructure systems (CIS) so that the role of public infrastructure is more central in SES research. This can be achieved by expanding ecologies of SES to include both built and natural components. We suggest that viewing SES as CIS provides a better reflection of the sustainability problem context in the modern era because of the prominence of infrastructure systems in contemporary SES. It would also help cross-fertilize knowledge between social and natural science-based sustainability scholars and those based in applied sciences of architecture and engineering. A better understanding of design criteria for robust CIS is crucial for sustainability research.

Of course, the findings of this chapter are preliminary and represent a first step toward better understanding the capacity of CIS to cope with global change. Our study restricted the number of strategies to two: group-conformist and opportunist. Additional strategies could be considered: for example, farmers could invest in the infrastructure but take more water than their allocated share. It is assumed that the depreciation rate of infrastructure is fast, i.e., no water is provided unless the infrastructure is repaired every year. An alternative approach would be to assume a slower rate of depreciation, such that some water is still provided even if no repair is done in a given year. These variations will further our understanding of the influence of infrastructure in SES dynamics. Finally, further case-study analysis and empirical field work, like that which motivated this modeling effort (see csid.asu.edu), are essential to support theoretical and practical results.

3. THE EFFECT OF SOCIAL INFRASTRUCTURE ON THE TRANSFORMATION OF SOCIAL-ECOLOGICAL SYSTEMS UNDER ECONOMIC GLOBALIZATION

3.1. Introduction

Studies of commons dilemmas have often focused on investigating factors that affect whether and how institutions succeed or fail in enabling collective action in social-ecological systems (SES) (Ostrom 1990, 2005a, NRC 2002). This work has typically been static in nature - the biophysical, social, economic, and institutional factors that define the context in which the agents interact are assumed fixed. Recently, scholars have begun to view commons dilemmas through a dynamic lens and focus on what factors affect the capacity of SES to cope with change. One way SES cope with change is through transformation, a process that occurs when ecological, economic, or social structures make the existing system untenable and a fundamentally new system is created in response (Walker et al. 2004).

In this chapter, I build on this foundation to explore transformation patterns of SES. **I examine the question of what factors help explain the persistence of effective collective action in the management of common-pool resources in SES under conditions that will likely be realized in the next few decades as a result of economic globalization. Specifically, I focus on the effect of organizational form (a kind of**

social infrastructure) on how SES transform when they are forced to reorganize by changes brought by economic globalization.

Scholars suggest that economic globalization will connect SES across multiple temporal and spatial scales, dramatically changing the context in which many self-governed common-pool resource (CPR) institutions operate (Young et al. 2006, Anderies and Janssen 2011). One of the ways that such global inter-connectedness can impact local self-governed CPR systems is by increasing the inflow of substitute goods for CPRs or the opportunity cost of labor that will reduce the salience of CPRs for local livelihoods (Poteete and Ostrom 2004, Araral 2009). Such changes in context will likely induce some self-governed systems to fail and subsequently transform rather than merely to adapt. In the process, social actors will likely be confronted with dilemmas linked to the release and reorganization of their natural capital. Some actors may prefer the immediate benefit of selling out natural capital and taking their share of the proceeds over the uncertain long-term benefit of maintaining cooperation in some alternative ways. **How will the existing design or form of organizational structure affect actors' decisions on reorganizing their SES under the novel conditions?** Systematic research on post-failure transformation process is rare in the commons literature (although see Abel, Cumming, and Anderies 2006), and the connection between different transformation paths and their determinants remains poorly understood (Rudel 2011).

In the literature, there are a number of studies that explore the reorganization of SES in a different light. For example, several case studies investigate the struggles of local SES subjected to novel disturbances such as increased market pressure (Wunder et al. 2008, Silva et al. 2010), flows of people or intruders (Pérez et al. 2011), or development (Wollenberg et al. 2006, Levang et al. 2007). These studies focus on particular aspects of disturbances and ensuing responses themselves rather than the details of transformation. In another set of studies, scholars exclusively analyze transformations (Olsson et al. 2004, Biggs et al. 2010, Gelcich et al. 2010). These studies, however, either do not involve CPRs or rely heavily on small-N cases related to very specific contexts. A single case study or small-N set of case studies can reveal rich insights about a particular setting but their findings cannot easily translate into broader theoretical analysis (Basurto and Ostrom 2009). Lastly, some studies approach the subject from the perspective of long-term vulnerability and transformation (Anderies 2006, Nelson et al. 2010). These studies rely on a small-N set of archeological cases populated with very coarse data and focus on aspects of hidden vulnerabilities that emerge when SES optimize for a particular set of disturbances. Further, none of the above studies cover how the design of social infrastructure affects the patterns of SES transformation.

This chapter complements the existing literature by examining 89 forest commons in the Geumsan region of South Korea (Kang 2001) and the designs of their social organizational structures linked to nested governance (Figure 3.1, Figure 3.3, and Figure 3.4). After persisting for hundreds of years, these self-governed SES all collapsed and underwent major transformations, e.g., conservation of natural capital, conversion to new community infrastructure, selling-out, etc., in the second half of the 20th century as South Korea developed economically. The major drivers of this change include (Figure 3.2): (1) the transition in the nation’s primary energy consumption from high dependence on forest resources to near-zero dependence; (2) the massive rural-urban migration driven by the search for better opportunities; and (3) the introduction of national-level forestation policies. Because this set of cases constitutes a relatively large-N dataset and provides accounts of a range of different transformations under globalization, a careful analysis may yield some general insights on the relationship between the transformation of SES and the design of organizational form.

This article tackles three research questions. First, what are the patterns of transformation undergone by the 89 self-governed systems? Unlike the dichotomous classification of either robust or collapsed SES (Anderies et al. 2004), transformations can involve multiple trajectories of change. Second, what are some of the key factors that influence the persistence of effective collective action in the management of shared resources as they undergo transformative change? We focus on the design of social organizational form linked to nested governance. Third, are there tradeoffs between optimizing to particular past conditions and transformative capacity (sensu Janssen et al. 2007)?. Here, we investigate whether self-governed SES that may have become robust to particular past conditions undergo less cooperative transformations when they face new challenges in this era of globalization.

3.2. Methods

3.2.1. The study system

The Geumsan region sits in the central inland of South Korea and encompasses 576 km^2. The landscape of the region is roughly characterized by a large central flat valley and surrounding mountain ranges with forests (Figure 3.1). Hundreds of villages are interspersed throughout the area. *Songgye* (pronounced like "song-geh") refers to traditional Korean forest organizations established for setting up community-owned mountainous forests to provide access to firewood and organic compost made from weedy plants growing inside forests (Kang 2001, Chun and Tak 2009). Many *songgye* operated in the Geumsan region for hundreds of years and played key roles for the sustainable management of forest commons until they became functionally obsolete in the mid-20th century (Kang 2001). Until the advent of fossil-fuels and commercial fertilizers, the lives of most commoners heavily depended on sourcing these forest resources (Kang 2001, Chun and Tak 2009).

The main role of a *songgye* (plural – *songgye*) as a resource management organization was to provide three important types of public infrastructure. First, *songgye* provided institutions in the form of appropriation rules. For example, cutting down trees for firewood was usually prohibited, and members could only collect brushwood or dead trees during specified time periods few times a year (Park 2000, Chun and Tak 2009). Second, *songgye* enabled communities to tackle challenges of infrastructure provision. Through *songgye*, a village as a whole could pool money together to purchase a mountainous forest as common property (Kang 2001). Villagers also cooperated through *songgye* to repair mountain trails, essential infrastructure for enabling the mobility of resource appropriators (Kang 2001). Thirdly, *songgye* facilitated monitoring of rule compliance and sanctioning of unauthorized activities. Some *songgye* had dedicated guards while others had staff or ordinary members playing dual roles for guarding against intruders or rule-breakers (Kang 2001, Chun 2003).

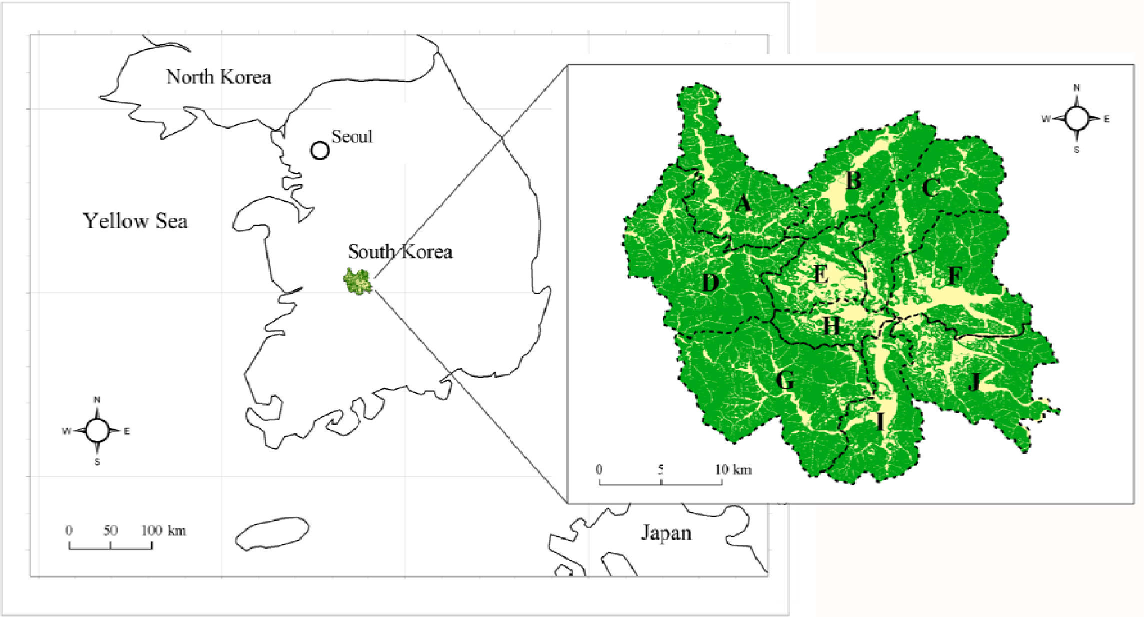

Figure 3.1. Map of Geumsan, South Korea. Light yellow area in the magnified map indicates the terrains of flat and lower slopes and roughly approximates the flat valleys. Green area indicates the mountainous terrains. The letters A to J in the magnified map indicate 10 administrative districts of Geumsan.

3.2.2. The drivers and consequences of change

With the onset of industrialization in South Korea from the 1960s and 70s, dramatic changes in context were imposed on the *songgye* of Geumsan. The nation's total demand for forest resources underwent a transition starting from this period. Prior to the industrialization, most South Koreans lived in rural areas and heavily depended on forest resources for home energy. For example, roughly 73% of the nation's annual primary energy consumption came from firewood during the period of 1955 to 1960 (bar chart,

Figure 3.2 A) (KCC 2001) and rural populations made up approximately 58% (14.6 million) of the 25 million people in 1960 (Bae and Lee 2006). However, in the 1960s and 70s, the use of coal briquettes began to spread widely across the country for residential uses (even in rural areas) and substitute firewood from the increased supply of coal briquettes, and the use of foreign-imported oil skyrocketed from the 1970s (KESIS 2013). The use of firewood dropped dramatically (blue portion of bars in Figure 3.2 A and by the period of 1981 to 1990, only 3% of the annual primary energy consumption came from firewood. South Korea also underwent a massive rural-urban migration since the late 1960s driven by the search for better economic opportunities in urban areas (Figure 3.2 B and C). By 1992, rural populations declined to approximately 13% (5.7 million) of the total population (BOK 2013). Driven in part by these trends, South Korea witnessed a striking turnaround in the nation's overall forest cover from net deforestation to net reforestation (Figure 3.2 A and B). The nation's average use of commercial fertilizers also increased substantially during this period from 162 kg/ha in 1970 to 458 kg/ha in 1990 (MAF 2005).

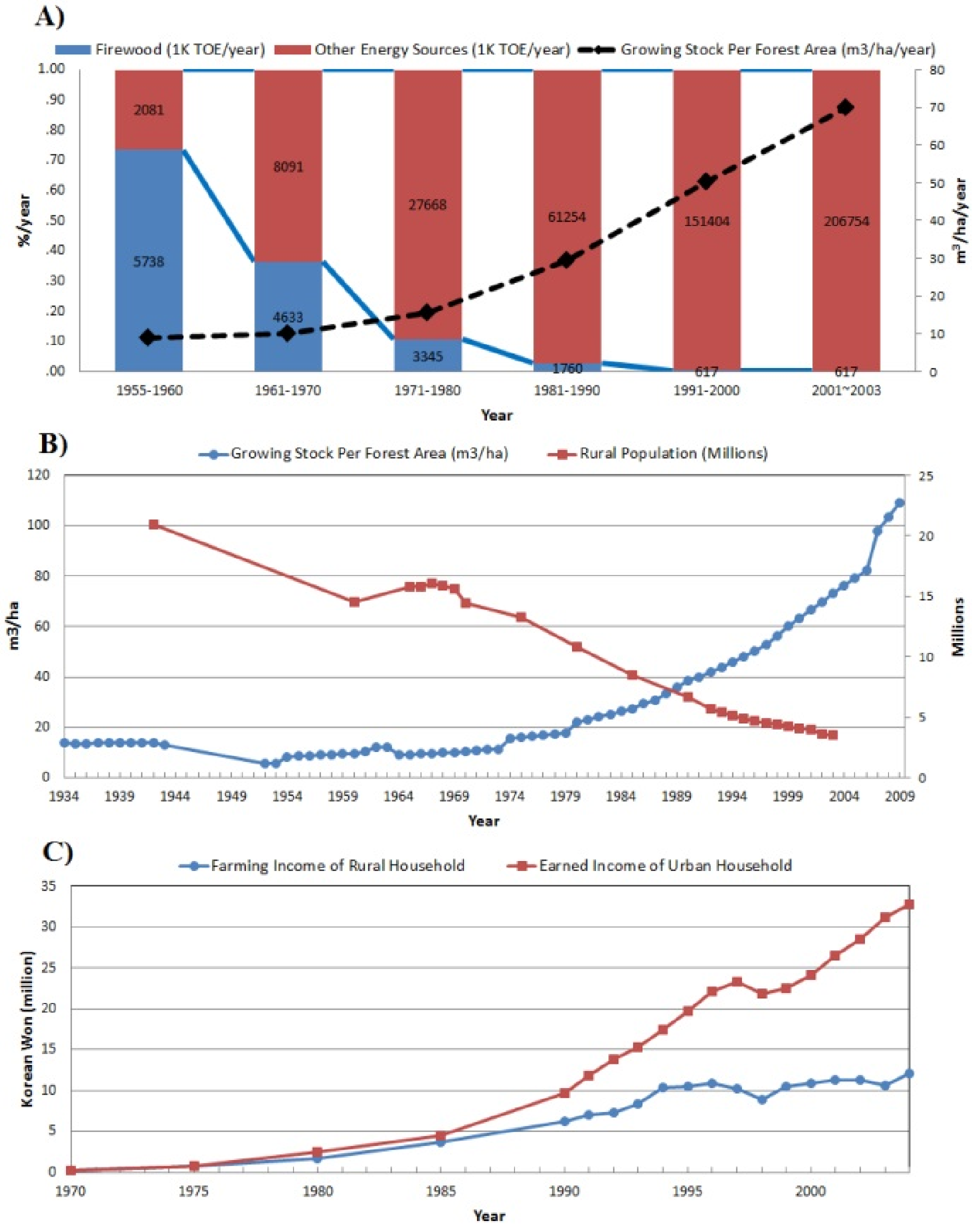

Figure 3.2. Changes in the broader context of *songgye* in South Korea. A. Trends in average primary energy consumption and volume of growing stock from 1955 to 2003 (Source: KCC 2001, KESIS 2013). Other energy sources include coal, oil, gas, nuclear power, and hydro-power (TOE: tons of oil equivalent). B. Trends in rural population and volume of growing stock from 1934 to 2009 (Source: Bae and Lee 2006, BOK 2013, KFS 2010). The lines between the markers are linear interpolations. Note that the data before 1952 concerns the entire Korean Peninsula. C. Trends in earned income of urban household and farming income of rural household from 1970 to 2004 (Source: MAF 2005).

These trends also affected Geumsan: the use of coal briquettes and commercial fertilizers gained wide adoption in the1960s and 70s and some of the more remote villages were deserted by the 1990s (Kang 2001). The overall forest cover of the area has also increased tremendously, jumping by a factor of 13.4 between 1976 and 2010 (see Table B.1 in APPENDIX B). These drastic changes in context most likely rendered the *songgye* in Geumsan obsolete from the early 1960s because of the tempered economic salience of the key forest resources that *songgye* were designed to govern (Kang 2001). In fact, no sightings of active *songgye* operations have been reported in the region from that period (Kang 2001). After their collapse, the *songgye* in the region reorganized themselves in a number of different ways. The nature of their reorganization is the focus of this paper.

At the same time, a number of shifting sociopolitical trends also affected the decisions of local villagers as they weighed different options for reorganizing their *songgye* (Kang 2001). Beginning in the 1960s, the Korean government introduced a series of regional and national level forestation plans to revitalize forests that were denuded by the Korean War and past overharvesting (Chun and Tak 2009, Bae et al. 2012). Rural villages were encouraged to organize tree-planting initiatives and to curb timber logging or other types of harvesting activities such as slash-and-burn farming. The government also rolled out concerted public campaigns to change the mental models of rural villagers. Slogans such as “planting is loving the nation” (Lee 2005) and “cutting trees is a menace and planting trees is an act of patriotism” (Bae et al. 2012) were directed at the general public.

In some cases, legal disputes arose over unclear property rights regarding *songgye* forests. These disputes originated from a colonial-period forest policy introduced to restructure the traditional forest ownership and tenure system during the Japanese occupation period (1910-1945). Under this policy, *songgye* mountains were denied for registration as commons. As such, many *songgye* in Geumsan had to register their forests as private properties under the names of village leaders (Kang 2001). This made the forests privately owned de jure but de facto commons. Finally, a real-estate boom pervaded the region throughout the 1980s and 90s (Kang 2001). As a side effect of economic development, the value of *songgye* forests as a real-estate commodity increased significantly around this time while the benefits that could be extracted from forestry became further obscured (Kang 2001). This shifting valuation most likely influenced the decisions of local villagers during the transformations of their *songgye*.

3.2.3. Data sources

We conducted secondary analysis of existing data collected for a previous research project on *songgye* (Kang 2001). Published and endorsed by the Geumsan Cultural Center, Kang (2001) is the only large-N qualitative study done to uncover historical evidence of *songgye* operation in the study site[2,3]. More important for our purposes, his study records how some of these *songgye* have reorganized themselves in

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[2] At present, Kang (2001) exists only in Korean Language. This book can be obtained at no charge from the Geumsan Cultural Center (http://geumsan.cult21.or.kr). The author of the book, Sungbok Kang, is currently full-time researcher at Chungnam National University in South Korea.

[3] FAO (2005) provides a similar historical case study about *songgye* in the Anmyoen-do region of South Korea.

the last 50 years. The 156 cases that are described by Kang (2001) offer a rare opportunity to explore general questions regarding the transformative capacity of SES subjected to relatively rapid change associated with globalization.

For the data collection, Kang (2001) primarily relied on oral histories, interviews with key informants, and archival research. The use of such qualitative methods of data collection are common in historical case studies of collective action related to natural resources (Poteete et al. 2010). Kang (2001)'s interview data came from 391 elderly local villagers who were identified to have some knowledge on the past practices of *songgye* as well as past village-level decisions related to the use of *songgye* forests. Of the 391 informants, 388 are men, most of whom were likely heads of their households. The average age of the informants was 73.9. The documentary evidence came from the archival materials that included contracts of property rights and transactions involving *songgye* forests, legal documents settling disputes, and writings of constitutions of *songgye*. Kang conducted the research over 10 years from the early 1990s to 2001, during which he visited the site 80 times for the fieldwork. Most of the interviews (98%) were conducted between 1998 and 2001.

For the secondary analysis, we subsample 89 cases based on two conditions: 1) time coincidence of transformation events with the onset of economic development (1960~) and 2) presence of key variables, e.g., outcome of transformation, size of resource system, etc. The first condition ensures that we are investigating transformative capacity under the influence of globalization. We thus restrict our analysis to the events that occurred in the period between 1960 and 1999. In the sample, 85 out of the 89 transformations occurred between the 1960s and 80s. Note that we are not further grouping these 89 cases even though different drivers of change may have been more important in different times. Our aim is to understand transformative capacity toward the general resilience of SES under the broader influence of globalization, not their specified resilience or robustness to specific disturbances (Folke et al. 2010). A word of caution about sampling bias is in order here. Because of the sampling criteria above, we are actually sampling on the cases of more persistent *songgye* than all representative ones. Hence, any causal claims made here should be interpreted in relative terms in the sense of the bias created here.

3.2.4. Methods and scope of analysis

Growing theoretical literature on collective action posits that a large number of contextual factors potentially affect the likelihood of individuals solving collective action problems (Agrawal 2002, Poteete et al. 2010). Here, to identify relevant contextual factors and to compare user interactions and outcomes across the sample, we employ the ontological framework of SES (Ostrom 2009; Ostrom 2007). Using the framework, we identify relevant similarities and differences in contextual factors and type of transformation among the sampled cases. Then, we search for plausible models for the relationship between type of transformation and contextual factors. Our approach reflects the methodological challenge raised by Basurto and Ostrom (2009) who assert that scholars should look for similarities and differences from rich details across multiple cases and combine theories to generate new hypotheses.

In our analysis, we focus on the roles of system-level factors, such as network diversity and biophysical context, rather than the details of community interactions that are often emphasized in small-N case studies. Our focus on system-level factors is motivated by recognizing that SES are complex adaptive systems (Levin and Clark 2010) in which emergent, system-level properties interact with individual-level processes to generate system dynamics. Of course, attributes of the community such as age and gender structure, existence of a local leader, and discussion during village meetings may affect the level of participation in community forest management (Lise 2000, Maskey et al. 2006). Thus, attributes of individual agents interact with biophysical context and rules-in-use in complex ways to produce governance outcomes (Ostrom 2005a). Our aim is to complement these earlier studies on attributes of the community and rules-in-use by exploring the effects of the system-level or structural factors on which these community details play out. Much work remains to be done to understand the effects of these system-level factors in the context of social-ecological transformation (Folke et al. 2010). We also note that details on the influences of gender and age structure and community interactions during village meetings on the villagers' decision-making were unavailable in Kang (2001)'s data. We suffer from a general limitation of all SES research: very few, if any, case studies exist that incorporate variables relating to all the components of SES articulated in the SES (Ostrom 2009) or Robustness (Anderies et al. 2004) Frameworks. As a result, we must use the data we have to study particular subsets of relationships within those frameworks.

3.3. Patterns of transformation

By the early 1960s, all *songgye* in Geumsan had become dysfunctional. In the ensuing post-failure reorganization phases, villagers interacted in the arena of village assembly meetings to decide the fate of their now-obsolete forests. The village assembly, an overarching village organization that oversaw all types of coordinated tasks in a single village, existed for every village in the region (Kang 2001). Depending on the number of participating villages in a *songgye*, either a single village or multiple villages interacted in the decision-making process. All member households of a village assembly could voice their opinions and, if voting was necessary for the decision-making, could cast a vote. In general, two broad types of actions were possible: 1) favoring short-term self-interest and 2) maintaining cooperative management in alternative ways. A village consensus (unanimous or almost unanimous agreement) or voting (some sort of majority rule) was generally used for decision-making at the village level, and the decision reached was binding for all members. When multiple villages were involved, decisions were usually made through two stages – each village would first decide on its preference and then all involved villages would have to agree unanimously if their shared assets were to be liquidated for other purposes (Kang 2001).

Four patterns of transformations are observed in the data. In pattern A, villages chose to maintain cooperative governance regimes and conserved their forests intact. In such cases, resource systems that had provided direct use values were essentially transformed into public goods with existence values. In pattern B, villages sold some or all of their forest resource systems and used the revenue raised to establish alternative community infrastructure. Examples include building village roads and bridges; purchasing lands for communal farming; constructing schools and community centers; and establishing communal funds (Kang 2001). In essence, these villages maintained their cooperative governance regimes in novel ways by converting their natural capital into new types of infrastructure that better met the modern-day needs of their communities. Pattern C is characterized by the release of some or all of the relevant natural capital with nothing contributing back to collective welfare. Motivated by short-term self-interest, villages in these instances sold their natural capital and simply divided among households the proceeds from the sale. In pattern D, instances of property right disputes motivated by unclear land titles are observed. Despite the possibility of settling the conflict and preserving their communal forests, villagers in these instances failed to generate enough collective action (collecting fees for upfront legal charges) to initiate formal legal actions. In such cases, resource systems fell into the hands of few opportunistic stakeholders (Kang 2001).

For our purposes, we further compact the four observed patterns into two broader patterns based on the degree of persistence of cooperation: 1) cooperative transformation and 2) non-cooperative transformation. In the cooperative transformations, the common-pool resources provided by the forest are transformed into public goods and cooperative governance is maintained in alternative forms (Pattern A and B). In the non-cooperative transformations, all of the forest resources are transformed into private gains, and cooperative governance is discontinued (Pattern C and D). This binary categorization constitutes our dependent variable in the statistical analysis. Our goal in the remainder of the paper is to confront the data and test whether there is a significant relationship between these patterns of transformation and the structure of SES.

3.4. Context of transformation

In this section, we discuss contextual factors that are judged to be important for affecting the patterns of transformation. These factors constitute the explanatory variables in our statistical analysis.

3.4.1. The design of social connectedness

A web of village-level social connectedness emerged in Geumsan as many villages developed social links with other villages to govern their *songgye* governance prior to the 20th century. These horizontal and vertical social linkages are built to create multiple centers of management and arrangements where collective action is organized in multiple layers of nested enterprises (Ostrom 1990, Cox et al. 2010).

In Geumsan, three historical strategies played key roles for the development of social linkages: 1) multiple-village cooperation, 2) diversity and redundancy in cooperative networks, and 3) vertical nesting within village assemblies. Multiple-village cooperation occurred whenever two or more villages formed an allied or federated *songgye* by co-purchasing a resource system and performing joint appropriation and provision activities under the supervision of a loosely formed inter-village council (Kang

2001) (*songgye* A in Figure 3.3 B and D). This practice reflects the design principle of nested enterprises in governing the commons (Ostrom 1990). We speculate that the resulting economy of scale and modularity of social systems better facilitated the provision of threshold public goods such as purchasing a large-scale mountainous forest and repairing mountain trails. For example, for purchasing forests, multiple villages acted together to increase their total group size and delegated each village to pool financial contributions from its member households. In this way, these allied villages were able to increase the level of the public good provision while decreasing the size of individual contributions and coordination costs. For the same reason, member villages of an allied *songgye* usually divided and maintained different sections of a network of forest trails (Kang 2001). In the cases where multiple-village cooperation did not occur, a single village solely managed a mountainous forest (*songgye* A in Figure 3.3 A and C).

Diversity in cooperative networks arose whenever villages participated in multiple instances of *songgye* simultaneously, which resulted in the creation of cross-institutional links across different *songgye* (*songgye* A in Figure 3.3 C and D). The resulting links of a village probably enabled that village to cope with varying biophysical conditions and uncertainties (due to redundant flows of forest resources) as well as gaining access to institutional diversity (for theoretical insights, see Elmqvist and Folke 2003, Folke et al. 2005, Anderies and Janssen 2011). For example, some villages with existing *songgye* forests that were either unproductive or too distant from their village locations chose to join another *songgye* in order to access more productive or nearer forests (Kang 2001).

Vertical nesting occurred whenever *songgye*-related affairs in a single village were nested under that village's assembly (Figure 3.4). Entire cases of *songgye* in Geumsan practiced vertical nesting (Kang 2001). We speculate that, through vertical nesting, a *songgye* could economize transaction costs by tapping into established leadership and legitimacy that already existed with village assembly. An additional layer of nesting occurred for allied *songgye* because they were coordinated by inter-village councils (Figure 3.4 B).

3.4.2. Village location

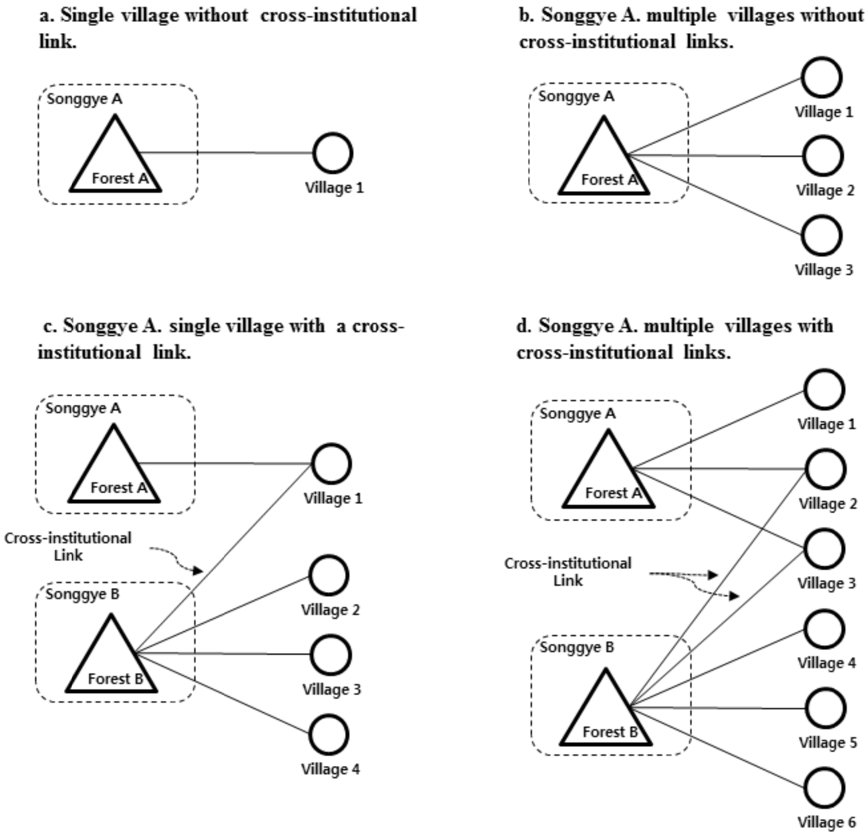
Depending on where villages are located, we speculate that the villages faced two biosocial heterogeneities in the past: 1) variation in availability of forest resources in their immediate surroundings and 2) variation in degree of village-to-village social connectivity.

Most of the villages in the central districts (district E and H in Figure 3.1) are located on flat areas, and therefore, lacked access to forests in their immediate surroundings. In the perimeter districts of B, C, F, I, and J, multiple types of landscapes are observed. Here, clusters of flat areas and mountainous terrains coexist in closer proximity. Kang (2001) suggests that the flat areas in the central and perimeter districts were more populous areas where villages tended to link seamlessly to one another without major spatial barriers. Most of the villages here probably had more neighboring villages and better inter-village social connectivity but less ease in finding harvestable forests nearby (Kang 2001). In contrast, most of the villages located in the mountainous areas (district A, D, and G and parts of district B, C, F, I, and J) tend to be isolated spatially by the natural barriers of mountain ranges. Inter-village social connectivity was probably lower there in the past, but these villages had better access to mountainous forests (Kang 2001).

3.4.3. Resource system and units

Songgye forests varied in terms of size and/or terrain characteristics. Some forests were large in area, encompassing as much as few hundred hectares. Some forests also differed in resource potential by having mostly rocky or gentle sloping terrains. Mainly harvested resource units were firewood and organic materials for composts. Some cases of *songgye*, however, were different in that they historically exercised considerable dry-field farming inside *songgye* forests as well as allowing outsiders to take over the farming in exchange for annual tenant fees (Kang 2001). In such cases, the collected fees became an important source of income for covering miscellaneous operating expenses of *songgye*.

As for the forest conditions in terms of volume of growing stock and composition of tree species, there may have been some variation across *songgye* forests between 1960 and 1999. However, such data is unavailable for our study, and the decisions of villagers were probably negligibly affected by these conditions. The dominant trend during this period is the declining user dependence on forest resources and the rise in forest cover regardless of the decisions selected by *songgye* users (see Figure 3.2 and Table B.1).


a. Single village without cross-institutional link.

b. Songgye A. multiple villages without cross-institutional links.

c. Songgye A. single village with a cross-institutional link.

d. Songgye A. multiple villages with cross-institutional links.

Figure 3.3. Types of village-to-*songgye* social connectedness. The link between a village and a forest represents a share in the property right of the forest and a participation in joint appropriation and provision activities. Triangles represent the biophysical boundary of the forest which is determined naturally by the physical boundary of a mountain along a contiguous range of mountains. The dashed rectangles indicate the institutional boundary of the *songgye*.

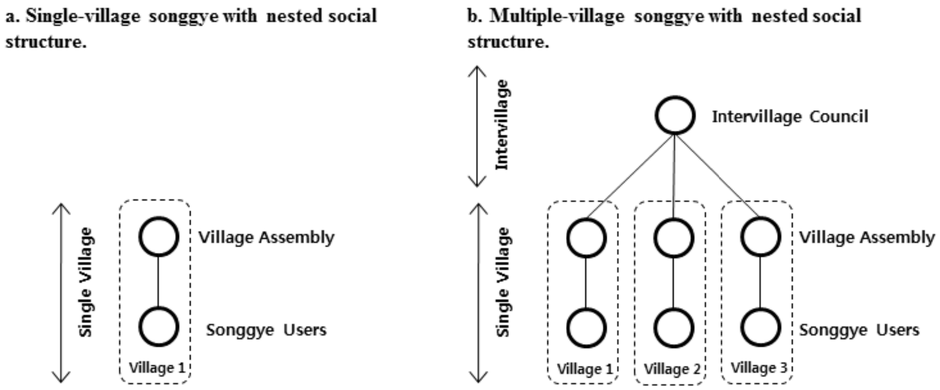


Figure 3.4. Types of vertical linkages in *songgye* social structure.

3.4.4. Summary: similarities and differences

Here, I outline some key similarities and differences (explanatory variables) across the cases for the period between 1960s and 90s. The notable similarities are reduced economic salience of CPRs due to emergence of substitute goods, rapid economic development, exposure to real-estate boom and reforestation policy by the government, unclear property rights, history of use, similar socioeconomic attributes of users, and decision-making through village assembly meetings. The key differences across the cases are outcome of transformation, number of horizontally linked villages, ratio of member villages with cross-institutional links, spatial extent of villages, topographic location of villages, size of resource system, terrain of resource system, and existence of tenant fees (for dry-field farming). Note that designed aspects of organizational form (a kind of social infrastructure) are characterized by the two variables:

number of horizontally linked villages and ratio of member villages with cross-institutional links.

Note that most of the similarities relate to the major drivers of change that were general and pervasive in nature. Because the *songgye* under study all derive from a single rural region that is mono-ethnic and -cultural in user characteristics, it is reasonable to assume that most of the *songgye* practically experienced the same level of shifting trends. Therefore, from a system-level perspective, notable differences across the cases mostly concerned the specifics of social connectedness and variations in villages' location, topographic position, and resource systems and units. Although the listed similarities and differences are not exhaustive, they largely cover the relevant information thought to be important for this research. Table 3.1 describes the variable definitions and measurements.

Table 3.1. Definitions of the contextual variables related to *songgye*.

Variables	Definitions
Dependent variable:	
Outcome of transformation	The outcome of transformation is categorized into two broad types: (1) cooperative transformation and (2) non-cooperative transformation (=1 if cooperative; =0 if non-cooperative).
Independent variables:	
Number of horizontally-linked villages	A number of villages in a *songgye* that are horizontally linked through shared property rights of a resource system and joint appropriation and provision activities. For the *songgye* 'A' in Figure 3.3 A and C, this measure is 1. In Figure 3.3 B and D, this measure is 3.
Ratio of member villages with cross-institutional links	The ratio of cross-institutional links measures the percentage of participating villages in a *songgye* that participate in multiple instances of *songgye* simultaneously†. For the *songgye* 'A' in Figure 3.3 A and B, this measure is 0. In Figure 3.3 C, this is 100%. In Figure 3.3 D, this is 2/3 or 67%.
Spatial extent of villages	The spatial extent is measured by the scale of administrative districts

	spanned by participating villages (=0 if one village is involved; =1 if multiple villages are involved but all are situated within one sub-district; and =2 if multiple villages are involved and are situated over multiple sub-districts).
Topographic location of villages	The percentages of flat areas in the surrounding areas of participating villages are averaged to derive this measure‡.
Size of resource system	The size of resource system measures the physical area covered by a *songgye*'s mountainous forest(s) (=0 if 1-10 hectares; =1 if 11-100 hectares; and =2 if greater than 100 hectares)§.
Terrain of resource system	The terrain type is estimated from the existence of considerable dry-field farming inside *songgye* mountains (=1 if considerable dry-field farming exists, i.e., presence of large mildly-sloping terrain; =0 otherwise).
Existence of tenant fees	The functional diversity carried by resource system is measured by the existence of annual tenant fees levied for the rights to exercise dry-field farming inside *songgye* mountains. It gauges whether or not the villages were able to extract extra benefits from their mountains (=1 if annual tenant fees were collected; =0 otherwise).

† Because these links in a given *songgye* can adjust over time as associated *songgye*undergo transformations, we take a snapshot of these links (taken at 1960) as our basis of analysis.
‡ Topographic position index (TPI) (Weiss 2001) is derived for each sub-district that contains member villages. For each sub-district, areas of flat and lower slopes are divided by the total sub-district area. This percentage is then averaged over all involved sub-districts.
§ The physical size is ordinal because some of the empirical cases provided estimated ranges of area instead of exact figures.

3.5. Data analysis

To relate the likelihood of cooperative transformation to the contextual factors, we used multivariate logistic-regression models. We used a model selection approach to hypothesis testing (Johnson and Omland 2004). We applied the Akaike Information Criterion (AIC) method (see APPENDIX B for details) to compare the fits of all possible combinations of explanatory variables (Burnham and Anderson 2002). AIC is calculated for a suite of models. The absolute size of the AIC is unimportant; instead the difference in AIC values between models indicates the relative support for the models. In order to compare models, we calculate Akaike weights (Burnham and Anderson 2002). We consider as plausible models those with Akaike weights that are within 10% of the highest weight. We also report the relative variable importance as the sum of Akaike weights over all models including the explanatory variable. The relative variable importance is the probability that, of the variables considered, a certain variable is in the best approximating model.

Lastly, we study correlations between topographic location of villages and their *songgye*-related social connectedness. If social connectedness is associated with topographic location and also with different trajectories of transformation, we could infer that optimizing for robustness (i.e., forming social connectedness) to past conditions (i.e., variations in resource flow stemming from topographic location) possibly affected the transformative capacity of *songgye* in the present day.

3.6. Results

3.6.1. Descriptive statistics

The majority (73%) of the transformations were cooperative: 36 cases of pattern A (40%) and 29 cases of pattern B (33%). The remaining transformations were non-cooperative: 19 cases of pattern C (21%) and 5 cases of pattern D (6%). The notable trends in descriptive statistics are the contrasts in the averages of a number of villages involved and ratios of cross-institutional links (Table 3.2 and Table 3.3). The average of the former factor among the cooperative transformations is lower (2.2) than its counterpart (6.3). The average of the latter factor among the cooperative cases is higher (0.6) than that of the non-cooperative cases (0.3). We now turn our attention to model selection techniques to explore the relationships between the explanatory variables listed in Table 3.1 and whether the transformation was cooperative or non-cooperative.

Table 3.2. Categorical variable statistics by cooperative and non-cooperative transformations. For details, see Table 3.1.

Variables	Non-cooperative transformation (N=24)			Cooperative transformation (N=65)		
	Frequency (%)			Frequency (%)		
	(=0)	(=1)	(=2)	(=0)	(=1)	(=2)
Size of resource system	5 (21%)	13 (54%)	6 (25%)	19 (29%)	36 (55%)	10 (15%)
Terrain of resource system	13 (54%)	11 (46%)		44 (68%)	21 (32%)	
Existence of tenant fees	6 (25%)	18 (75%)		25 (38%)	40 (62%)	
Spatial extent of villages	11 (46%)	5 (21%)	8 (33%)	42 (65%)	10 (15%)	13 (13%)

Table 3.3. Continuous variable statistics by cooperative and non-cooperative transformations. For details, see Table 3.2.

Variables	Non-cooperative transformation			Cooperative transformation		
	Mean	Std. Dev.	Min, Max	Mean	Std. Dev.	Min, Max
Number of horizontally-linked member villages	6.330	9.020	0, 39	2.185	2.567	1, 16
Ratio of member villages with cross-institutional links	0.344	0.423	0, 1	0.561	0.486	0, 1
Topographic location of villages	0.244	0.127	0.051, 0.558	0.221	0.119	0.051, 0.610

3.6.2. Model selection

The model selection results suggested that 20 models could be considered as plausible (Table 3.4). Given the data and set of candidate models, the best explanatory model is the one that included *number of horizontally-linked villages* and *ratio of member* *villages with cross-institutional links*. The former variable was included in all of the plausible models with a negative response. The latter variable had a probability of 0.87 of being in the best approximating model with a positive response. Thus, cooperative outcomes were associated with lower number of horizontal villages and higher proportion of cross-linked villages. *Existence of tenant fees* had a probability close to 0.5 of being in the best model and with the previous two variables formed the second plausible model. The association of outcomes with *existence of tenant fees* was negative. The third model added *terrain of resource system* to the best model. This variable had a probability of 0.31 with a negative coefficient. The fourth model added *topographic location of villages* to the best model. This variable had a probability of 0.32 of being in the best fitting model and its response was negative. S*ize of resource system* was added in the fifth plausible model. This variable had a probability of 0.31 with a positive coefficient. Finally, *spatial extent of village*s first appears in the 17th plausible model. This variable had a low probability (0.14) of being in the best fitting model with a positive coefficient. See Table B.2 for the variable values used in the model selection.

Table 3.4. Plausible models identified by the AIC method. For each model, the table indicates the coefficient of the variables included, the number of parameters (df), log-likelihood (logLik), delta weight (ΔAIC, difference between the AIC for a given model and the AIC of the best-fitting model), and Akaike weights (w, the model selection probability). Averaged coefficients and the relative variable importance are also presented. The Akaike weight is the probability that a model would be selected as the best-fitting model if the data were collected again under identical circumstances. Model averaged estimates are weighted by their Akaike weight.

Model	df	(Intercept)	Spatial extent of villages	Existence of tenant fees	Topographic location of villages	Number of horizontal villages	Ratio of cross-institutional links	Terrain of resource systems	Size of resource system	logLik	ΔAIC	*w*
1	3	1.1059	-	-	-	-1.0601	0.6322	-	-	-44.09	94.19	0.12
2	4	1.1254	-	-	-	-1.1117	0.6114	-	-	-43.24	94.47	0.10
3	4	1.1091	-	-0.3664	-	-1.0242	0.6667	-0.2176	-	-43.78	95.55	0.06
4	4	1.1163	-	-	-0.2259	-0.9973	0.7214	-	-	-43.85	95.70	0.06
5	6	0.9612	-	-0.4227	-	-1.5737	0.6889	-	-0.0923	-41.88	95.75	0.05
6	5	1.1409	-	-0.3863	-0.2598	-1.0257	0.7069	-	-	-42.91	95.82	0.05
7	5	0.8885	-	-	-	-1.4457	0.7125	-	0.0064	-42.93	95.85	0.05
8	5	1.1254	-	-0.3348	-	-1.0959	0.6264	-0.0710	-	-43.21	96.42	0.04
9	6	0.8829	-	-	-	-1.4584	0.7606	-0.2790	-0.0081	-42.43	96.86	0.03
10	5	1.1238	-	-	-0.2585	-0.9443	0.7760	-0.2464	-	-43.46	96.91	0.03
11	7	0.9199	-	-0.4429	-0.2941	-1.5067	0.8027	-	-0.0218	-41.48	96.96	0.03
12	6	0.8402	-	-	-0.2638	-1.3957	0.8240	-	0.08224	-42.61	97.22	0.03
13	3	1.0528	-	-0.4015	-	-0.9802	-	-	-	-45.70	97.40	0.02
14	2	1.0207	-	-	-	-0.9109	-	-	-	-46.78	97.56	0.02
15	7	0.9530	-	-0.3676	-	-1.5649	0.7160	-0.1257	-0.0908	-41.79	97.59	0.02
16	6	1.1420	-	-0.3444	-0.2674	-1.0029	0.7315	-0.0942	-	-42.87	97.73	0.02
17	5	0.9564	1.0000	-	-	-1.2842	0.5691	-	-	-43.92	97.83	0.02
18	7	0.8127	-	-	-0.3069	-1.4014	0.9021	-0.3128	0.1034	-42.00	98.00	0.02
19	6	0.9913	1.0000	-0.3573	-	-1.3017	0.5583	-	-	-43.11	98.22	0.02
20	8	0.8989	-	-0.3745	-0.3068	-1.4952	0.8450	-0.1518	-0.0017	-41.36	98.73	0.01
Averaged coefficients		1.0230	0.0046	-0.1788	-0.0802	-1.2054	0.6007	-0.0536	-0.0110			
Relative variable importance		1.00	0.14	0.46	0.32	1.00	0.87	0.31	0.31			

3.6.3. Linking social connectedness and biophysical context

We ran correlation analyses to test whether the biophysical context (topographic location) of a village is associated with its social connectedness. We first tested the association between the topographic location[4] of a village and the group size of each *songgye* (number of villages) that the village belonged to[5]. The association is significant (p-value < 0.001) with a modest correlation (Pearson's r=0.365). This suggests that villages situated on a flat valley are more likely to be a member of an allied *songgye* (e.g., *songgye* A in Figure 3.3 B and D) than villages located in mountainous areas. This make intuitive sense: with more neighbors and less resource availability in its immediate surroundings, a village located in a valley probably had more incentives to cooperate with others to economize costs of operating a *songgye*. The association between the topographic location and whether a village carried at least one cross-institutional link is not significant (p-value > 0.05).

3.7. Discussion and conclusion

This research began with the assertion that given the process of globalization now underway, the study of the commons needs to not only address whether cooperation

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[4] Topographic position index (TPI) (Weiss 2001) is derived for each sub-district that contains member villages. For each sub-district, areas of flat and lower slopes are divided by the total sub-district area to derive the percentage of flat terrains.

[5] Here, our unit of analysis is associations between a village and its participations in one or more *songgye*. Because we are dealing with past robustness, we apply all 156 cases of *songgye* as the sample. Since some villages joined more than one *songgye*, the total count of associations is 501 (although the total number of villages is 338).

arises or fails in a given set of biophysical, social, and economic circumstances, but also to begin to understand the dynamics of cooperation as those circumstances change. Here, I examined some dimensions of post-failure processes and the question of what factors help explain the nature of post-failure transformation of self-governed CPR systems. In particular, I focused on the effect of the design of organizational form linked to nested enterprise. In the current body of literature, we found no studies that directly attempted to answer this question in a structured way. Most of the studies either focused on relationships among aspects of specific disturbances, responses, and vulnerability tradeoffs or depended on either a single or a small-N set of cases that could not offer understanding of underlying structure for observed patterns of transformation in a statistically significant way.

From analyzing 89 *songgye* in Geumsan that underwent transformations under globalization, we observed two broad categories of transformation: cooperative and non-cooperative transformations. The majority of the observed transformations are cooperative (65 out of 89). The presence of these two broader trajectories of transformation simply reflects the nature of a dilemma faced by the users: whether to continue to pursue some form of social welfare as they had previously or opt for private gains. The fact that the majority of the observed transformations are cooperative may be explained by the sampling bias we introduced by selecting only those *songgye* that remained intact until the early 1960s, which implies that our sample probably consisted of villages that were inherently high in social capital. Such higher levels of social capital probably enabled many villages to pursue some form of collective welfare in spite of the apparent temptation to pursue individual gains during transformations.

Second, the best-fitting model shows that cooperative transformations are negatively correlated with number of horizontally-linked villages in a *songgye*. On the other hand, cooperative transformations are positively associated with the ratio of member villages with cross-institutional links. The opposite is true for non-cooperative transformations. The direction of association exhibited by the number of villages in a *songgye* is consistent with the transaction cost hypothesis of group size—the more participants there are in a collective action problem, the more difficult it is to organize collective action due to higher coordination or transaction costs (Poteete and Ostrom 2004, Araral 2009). Because participant villages in a *songgye* act cohesively as single actors at the system-level, the number of member villages is a scale-invariant representation of group size. As such, *songgye* with higher counts of member villages probably faced greater transaction costs and thus were less likely to maintain collective action through transformations. This speculation is consistent with the observed patterns in our sample data. One might ask then why such *songgye* with large group sizes even existed in the first place. In the past, this type of social infrastructure design was probably possible or even welcomed because the salience of forest resources for villager livelihoods was high and the necessary public infrastructure, e.g., mountain trails, were threshold public goods that required economy of scale in contributions of human effort.

What we find more interesting is the positive association between the ratio of member villages with cross-institutional links and the prospect of villages engaging in more cooperative transformations. Such links emerged when the villages in Geumsan participate in multiple instances of *songgye* simultaneously. We speculate that these villages with cross-institutional links may have functioned as bridging actors or connectors who facilitated information exchanges and brought in networks of contacts that helped local communities to gain access to new ideas and resources as well as institutional diversity (Westley 1995, Folke et al. 2005). In the past, these villages probably fostered circulation of more diverse and up-to-date knowledge useful for governing forest commons sustainably. Similarly, in the modern-day situations of transformation driven by globalization, the presence of such connectors probably mitigated the problem of information uncertainties regarding available trajectories of transformation and the associated costs and benefits. For example, the presence of bridging villages may have better facilitated circulation of information regarding the serviceability of new community infrastructure that villagers weren't aware of, what the social value of a conservation or alternative public infrastructure could be, or what the expected market value of a forest might have been if sold.

Next, we find some evidence that there was a potential tradeoff between robustness and transformative capacity of *songgye*. Our analysis shows that the topographic location of a village and the number of its horizontal links are significantly associated. Given that this connectedness resembles the organizational structure for nested entperise which are known to enhance adaptive capacity and thus robustness of social systems (Ostrom 1996, Folke et al. 2005, Marshall 2008), we could infer the following: such connectedness evolved in Geumsan in part because of the villages' efforts to enhance robustness of resource flows to variation associated with the biophysical context in which they operated. In the past, the emergence of such context-dependent connectedness probably gave those *songgye* more robustness to uncertainty in resource flows. For example, from the horizontal links, such *songgye* probably had more local adaptability and economy of scale for providing collective goods. However, when pressures associated with globalization finally necessitated transformations, the advantages of horizontal links no longer applied and the transaction costs associated with horizontal links may have dominated the transformation action situation.

Lastly, we reflect on the effects of the remaining independent variables. Although these variables were absent in the best-fitting model, we can make the following assessments. The negative associations of the cooperative outcomes with *existence of tenant fees*, *terrain of resource system*, and *topographic location of villages* may imply that when these variables have larger values, the forests probably have more favorable terrains and locations and thus more potential for alternative uses. This could mean higher opportunity costs for transforming cooperatively. Contrary to our expectation, *existence of tenant fees* is negatively associated with the cooperative outcomes. A possible explanation is that slash-and-burn farming was strongly curbed by the national-level forestation policies from the early 1970s, meaning no more revenue from tenants (Bae and Lee 2006). The positive associations of the cooperative outcomes with *size of resource system* and *spatial extent of villages* may be explained by the observation that some *songgye* with large-scale resource systems spread over multiple sub-districts chose to informally sub-divide their forests among their member villages (Kang 2001). This informal sub-division of shared property rights could have given those member villages more incentives for transforming cooperatively.

From the above analysis, some conclusions may be drawn about the transformative capacity of SES subjected to the growing extent and intensity of global interconnectedness. When self-governed CPR systems become untenable as a result of globalization, systems with lower transaction costs, i.e., those with smaller group size, and higher network diversity, i.e., more ties to others through linkages such as cross-linked property rights or shared institutional memory, are more likely to organize transformations that still preserve some form of collective welfare. Conversely, previously highly efficient systems that relied on economy of scale and undivided participation from multiple social systems through nested enterprise may become more vulnerable to transforming uncooperatively when they become untenable. Certainly, the present paper is limited in scope. Further studies on other contexts may find different empirical patterns and different variables to be more important. However, we emphasize that the accumulation of different insights from different contexts and their comparisons including ours will only lead to a fuller understanding on the transformative capacity of SES.

4. WHAT CHARACTERIZES EFFECTIVE ADAPTIVE MANAGEMENT OF SOCIAL-ECOLOGICAL SYSTEM UNDER UNCERTAINTY? EVIDENCE FROM A LABORATORY BEHAVIORAL EXPERIMENT

4.1. Introduction

Managing a complex social-ecological system (SES) under global change is an endeavor fraught with high degrees of uncertainty (Dietz et al. 2003). Over the years, scholars have come to agree that a learning-focused approach such as adaptive management is necessary to deal with the uncertainty and complexity of SES management (Folke et al. 2010, Polasky et al. 2011). In adaptive management, the process of learning-by-doing is a key condition for success—an iterative decision-making process in which decision-makers adapt to changing conditions and new information by constantly learning from re-evaluating past assumptions and actions (Walters and Holling 1990, Gunderson 1999, Lee 1999). In addition, a large volume of literature suggests that several other conditions or processes contribute to the social capacity necessary to implement adaptive management. These conditions include, for example, user participation (Armitage et al. 2009, Plummer et al. 2012), monitoring and reflection (Armitage et al. 2008), leadership (Folke et al. 2005, Gutiérrez et al. 2011) and knowledge generation (Berkes 2009), among others. These conditions likely characterize exemplary features of adaptive management linked to SES resilience (Walker et al. 2004, Folke et al. 2010) or robustness (Anderies et al. 2004).

However, after three decades of research on adaptive management of SES, the question of what type of learning-by-doing is most effective and under what conditions still remains largely unanswered (Biggs et al. 2012, Fabricius and Cundill 2014). That is, although our theoretical understanding on each of the conditions related to adaptive management is considerable, how these conditions combine to differentially affect SES adaptability in the face of uncertainty is poorly understood. What are appropriate configurations of learning-by-doing and supporting conditions? Do such configurations vary depending on the presence or absence of uncertainty? This study examines these questions using a laboratory behavioral experiment of SES. Human-subjects of our behavioral experiment face a decision problem on collective management of an irrigation infrastructure under environmental uncertainty. By observing how they iteratively deliberate and learn to solve the decision problem under uncertainty, we tried to uncover some of the causal configurations of the conditions linked to successful adaptive management of SES.

We used the experimental data from a laboratory irrigation experiment that was conducted for another study (Anderies et al. 2013a). A large number of undergraduate students in a U.S. university (21 groups of five participants) participated in the experiment in 2010. Following the Institutional Analysis and Development (IAD) Framework (Ostrom et al. 1994), our irrigation experiment is designed to have the biophysical characteristics and the structure of action situation that mirror collective management of a farmer-managed irrigation system (Yoder 1994) in a developing context. The participants tackled the management decision problem through multiple rounds of group discussion, management actions, and sensing outcomes of those actions, while facing environmental uncertainty in selected rounds. This repeated cycle of the steps most likely facilitated the participants to engage in an iterative learning-by-doing to manage their irrigation system. Hence, a careful analysis of the experiment data may provide empirical clues to identifying what type of learning-by-doing is most effective and under what conditions for successful adaptive SES management. Controlled behavioral experiments in a laboratory setting are typically used to study specific hypotheses about human behavior in collective action situations (Poteete et al. 2010). Although this type of experiments does not involve actual stakeholders in a real field setting, it has confirmed numerous observed phenomena in field studies and contributed to theoretical developments in the study of human behavior in the use of common-pool resources and public goods (Poteete et al. 2010).

The action situation of the experiment captures the essence of collective action problems associated with managing a farmer-managed irrigation system. In a typical system, farmers convey water from its source through production infrastructure (weir) and distribution infrastructure (canals) to produce food. But such action situations pose two types of decision problems on farmers (Ostrom and Gardner 1993, Dayton-Johnson 2003). First, farmers must mobilize a substantial level of collective labor to repair the infrastructure each year (canals must be cleaned of debris and damaged water diversion structures must be fixed). If too few farmers participate in the collective repair work, the irrigation system stops functioning and everyone loses out (a threshold public goods dilemma). Secondly, farmers must coordinate for fair water distribution, which can be undermined by upstream-downstream asymmetry stemming from the canal layout (an asymmetric commons dilemma). If upstream farmers do not share water, downstream farmers are left with little or no water. In such cases of inequality, downstream farmers who do not get enough water often retaliate by not contributing labor to the infrastructure (Ostrom and Gardner 1993, Janssen et al. 2011a). Participants in our experiment played 20 rounds of that action situation. In the initial 10 rounds, they encountered the decision problem under environmental certainty, i.e., the rate of water supply feeding the infrastructure and the annual decline or deterioration rate of the infrastructure were fixed. However, in the latter 10 rounds, they faced the same decision problem under environmental uncertainty, i.e., the water supply rate or the infrastructure decline rate was fluctuating.

Group communication is an important part of our experiment, i.e., participants engage in group discussion before making the decisions in every round. Among the diverse factors that are known to foster collective action, the opportunity to communicate has been consistently revealed to be the most critical of these factors (Sally 1995, Cardenas et al. 2000, Janssen et al. 2010). However, in contrast to the voluminous scholarship on the effects of communication on collective action, there have been relatively few studies on the effects of communication on the adaptability of SES. Our research explored the role of communication on SES adaptability by categorizing and mapping different types of group communication content to some of the conditions related to adaptive management (different types of learning-by-doing, user participation, knowledge generation, monitoring and reflection, and group coordination). By mapping such linkages, we tried to identify potential causal configurations of the conditions tied to SES adaptability.

Previous studies based on the similar experimental setup found that individuals in small groups (5 participants) can successfully manage the irrigation system if allowed to communicate (Janssen et al. 2011a), individuals are willing to tolerate some inequality in the amount of appropriated irrigation water as long as there is some proportional equivalence between investments in and benefits from the irrigation infrastructure (ibid), and that unequal sharing of irrigation water under environmental certainty may cause collective action to be more fragile under environmental uncertainty (Anderies et al. 2013a). It was also found that the presence of certain combinations of social roles (e.g., leader, knowledge-generator, moralist) may influence a group's level of collective action (Pérez et al. 2013). This study complements the previous studies by examining how participants' prior experience with some emergent conditions of iterative management process under environmental certainty affect their capacity to manage the irrigation system in times of environmental uncertainty.

We measured two types of individual and group-level learning using the experimental data: inner-loop (or single-loop) and outer-loop (or double-loop) learning processes (Argyris and Schön 1978, Pahl-Wostl 2009, Rodela 2011). These learning types, visualized by the recursive processes in Figure 4.1, are known to help SES management in different ways. Learning-by-doing through the inner-loop is defined as involving revisions or updating of specific strategies or actions to better meet existing goals or assumptions. This process focuses on the question: are we as a group doing things right? Learning-by-doing through the outer-loop entails change in underlying goals or assumptions that underlie specific strategies or actions. The question here is: are we as a group doing the right things? The iterative process of decision-making and learning has long been regarded as a central condition of adaptive SES management (Fazey et al. 2005, Levrel and Bouamrane 2008, Reed et al. 2010, Tschakert and Dietrich 2010). In particular, learning-by-doing at the level of social learning—learning that goes beyond individuals to become situated within wider social units through social interactions—is thought to be essential for success (Reed et al. 2010, Rodela 2011). The participants of our irrigation experiment likely engaged in learning-by-doing at the level of social learning, i.e., they interacted through group discussions and engaged in decision-making and learning.

A large volume of literature also highlights the importance of several other conditions such as user participation, exchange of knowledge, and continuous monitoring and reflection (Armitage et al. 2009, Plummer et al. 2012, Fabricius and Cundill 2014). User participation, defined as process whereby individuals, groups, or organizations actively engage in decision-making, is considered central to co-management (Reed 2008, Armitage et al. 2009). User participation is known to stimulate a group's capacity to learn, and thus likely contributes to SES management (Cundill 2010). It is also not surprising that active sharing or exchange of knowledge is linked to better group capacity to learn and adapt (Berkes 2009, Newig et al. 2010). Further, through monitoring and reflection, actors continuously compare and evaluate the effects of their management actions. Monitoring and reflection enable the dynamic feedback process that is essential for adaptive management (Fabricius and Cundill 2014). Finally, group coordination among users likely represents the level of collective action or social cohesion in a group. Group coordination could be interpreted as an outcome of learning-by-doing, but it may also occur without it. Tight group coordination for management action can lead to more robust SES (e.g., Cifdaloz et al. 2010).

We measured all of the above conditions by analyzing the content of group communication and the decisions of the participants. Which configurations of the above conditions lead to more robust SES? Does every condition need to be present? In particular, is there a configuration that works under certainty but fail under uncertainty? Analysis of our experimental data may provide clues to these questions.

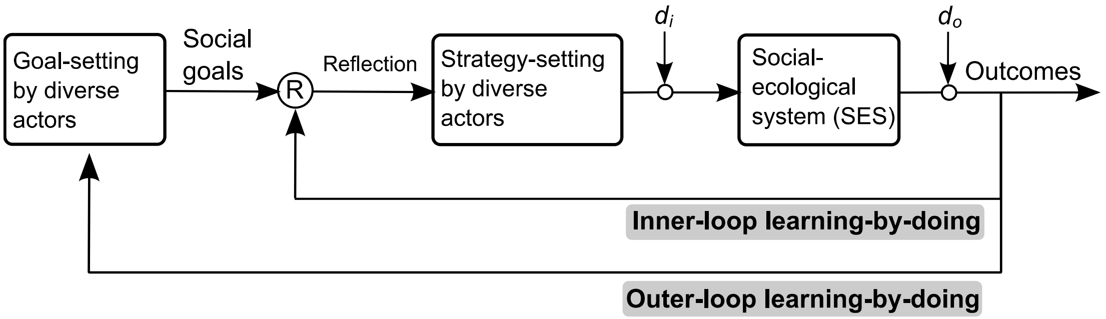


Figure 4.1. Learning-by-doing through inner-loop and outer-loop processes in a social-ecological system. The inner-loop processes is for controlling specific management strategies. The outer-loop process updates shared goals or assumptions that underlie specific management actions. The circle with letter R represents the process of reflection. The arrows denoted by d_i and d_o represent internal and external disturbances, respectively. This figure is adapted from Pahl-Wostl (2009) and Anderies (2014b).

This chapter progresses through two stages. First, we analyzed both the content of group discussion (qualitative data) and the decisions and outcomes of the participants (quantitative data) to identify which configurations of the conditions may be causally linked to group performance (level of group earnings from the irrigation system) under environmental certainty. Second, we explored which configurations may be causally linked to the robustness of group performance under environmental uncertainty. We used the analytical method of fuzzy-set qualitative comparative analysis (fsQCA) to identify potential causal configurations. The results of our fsQCA highlight the importance of learning-by-doing at the level of the outer-loop—updating of goals or assumptions that underlie specific strategies or actions. Active adapting of goals or assumptions may be a necessary condition for robustness under uncertainty.

4.2. Methods

4.2.1. Experimental action situation

Our research data are from a laboratory irrigation experiment conducted at Arizona State University in 2010 (Anderies et al. 2013a). A randomly-recruited sample of 105 undergraduate students (21 groups of five participants) from various majors participated in the experiment. The experiment was administered through a computer interface that emulates the essence of collective action problems associated with managing a farmer-managed irrigation system. Each participant sat in a study cubicle with a computer during the experiment, and was instructed not to verbally speak with their neighbors or see others' computer screens. How a participant performed in the experiment (i.e., earn tokens from managing and using the irrigation system) was directly linked to monetary rewards he or she received at the end of the experiment ($0.05 per token), i.e., salience. Hence, each participant faced incentives to make decisions that increase his or her tokens earned.

The experiment began with a moderator reading out instructions to the participants about the rules and procedures of the experiment, followed by a short quiz that tested how well they understood the experiment. Next, each group of five participants played two rounds the experiment as practice. Finally, each group went through 20 rounds of the action situation linked to monetary rewards. Each round is comprised of the following three steps.

In the first step, all participants in a group enter into group discussion for 60 seconds. They use a computer chat interface to communicate with others in the same group. They typically engage in discussions about the following subjects, among others: conditions of the irrigation system, outcomes or behaviors of individuals and the whole group in previous rounds, specific group strategies to deploy in the second step (how much tokens to invest for maintaining the irrigation infrastructure) and the third step (how to coordinate among themselves to harvest water from the irrigation infrastructure), shared goals or assumptions to achieve (e.g., equal harvesting of water, optimal maintenance of the infrastructure), supporting information or knowledge about the action situation, and how to correct behaviors of specific participants that deviate from shared strategies. In short, group discussion is the main arena through which social interactions occur for managing the irrigation system.

At the start of the second step, each participant receives an endowment of 10 tokens. He or she must decide how much of this endowment to invest for maintaining the infrastructure or for keeping. Un-invested tokens yield a fixed return of $0.05 per token. This investment decision can lie anywhere between two extremes: invest all for the infrastructure maintenance and keep all for the fixed return. In round 1, the infrastructure is initialized to 75% efficiency. Note that investments are regularly needed to repair the infrastructure because its efficiency declines at a certain rate every round. This decline mirrors the natural wear-out of irrigation infrastructure from accumulation of debris in canals or washouts of water diversion structures from flash floods. Normal rate of the efficiency decline is 25% per round. Investment of one token restores the efficiency by 1%. This means that at least 25 tokens are needed every round to stop the net decline of the infrastructure efficiency.

The relationship between the infrastructure efficiency and the water delivery capacity of the infrastructure (cubic feet of water per second) is of sigmoid shape (Figure 4.2 A). The infrastructure must have at least 46% efficiency to start to convey water. However, beyond 61% efficiency, the infrastructure faces diminishing return in delivery capacity as additional investments are made to increase the efficiency. Note that the water source (e.g., river, reservoir) normally supplies 30 cubic feet of water per second to the infrastructure. This means that, under the normal conditions, it is optimal to maintain the infrastructure at 66% efficiency (i.e., synchronizing the water delivery capacity and the water supply rate at 30cf/s) and invest 25 tokens every round to compensate for the infrastructure decline of 25%. If the infrastructure efficiency drops below 66%, the delivery capacity falls below the available water supply .

This investment decision problem faced by the participants is essentially a threshold public goods dilemma. To make the infrastructure perform, collective investments are needed because no one can single-handedly maintain the infrastructure (i.e., 25 tokens are needed to balance the efficiency decline of 25% but a single participant is endowed with only 10 tokens). However, the benefit of investment (water diverted and conveyed by the infrastructure) is open to all participants regardless of their investment levels. Thus, self-interested rational actors would invest zero tokens and attempt to free-ride by taking water without investment.

In the third step, participants in a group harvest water from the infrastructure over the period of 50 seconds to produce crop, which yields tokens. They open and close water gates to their fields in the computer interface to harvest water (Figure 4.3). An opened gate can take water at a maximum rate of 25cf/s. The relationship between water harvest and crop production (tokens earned) is of inverted-U shape (Figure 4.2 B). Crop production is maximized at 500-549 cf of water harvest. Beyond this interval, additional water harvest leads to reduced crop production because of adverse effects, e.g., water logging. It is crucial to note that there are five participants (denoted as participant A, B, C, D and E in the computer interface) in a group, and that they are heterogeneously located along the irrigation canal from the water diversion point (Figure 4.3). Participant A is closest to the water or at the most upstream location, while participant E is furthest from the water source or at the most downstream location. This heterogeneity in location leads to the so-called asymmetric commons dilemma, i.e., benefit is available to all, but individuals are heterogeneous in their capacity to obtain the benefit. In such a setting, advantaged individuals are tempted to take more benefit than others, which subtracts from what is available to others. Thus, self-interested rational participants in upstream locations would take as much water as they can (500~549cf of water), leaving little or no water for downstream participants.

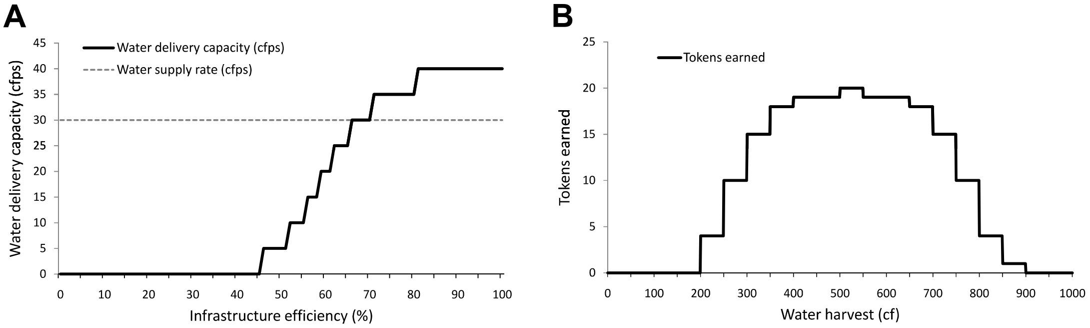
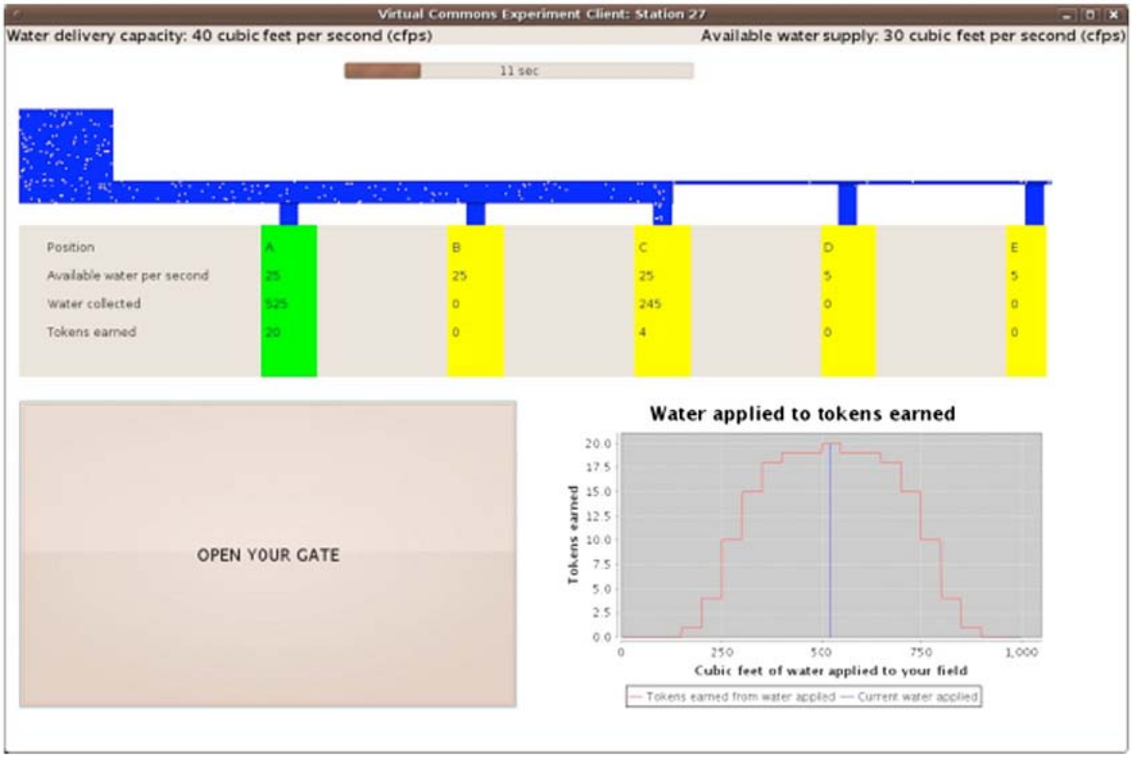


Figure 4.2. Biophysical rules associated with the infrastructure investment and water harvest activities in the irrigation experiment. Panel A shows that the relationship between infrastructure efficiency and water delivery capacity is of sigmoid shape. Panel B shows that the relationship between water harvest and tokens earned from crop production is of inverted-U shape.



Virtual Commons Experiment Client: Station 27

Water delivery capacity: 40 cubic feet per second (cfps)

Available water supply: 30 cubic feet per second (cfps)

11 sec

Position	A	B	C	D	E
Available water per second	25	25	25	5	5
Water collected	525	0	245	0	0
Tokens earned	20	0	4	0	0

OPEN YOUR GATE

Figure 4.3. Interface for water harvest in the irrigation experiment. Five participants with heterogeneous positions (position A, B, C, D and E) are located along the canal (blue-colored water pipe with white bubbles). Participants can open and close their gates to harvest water. Note that position A is closest to the water or at the most upstream location. Participant E is farthest from the water or at the most downstream location.

Each group played the first 10 rounds of the experiment under the normal conditions or stable environment, i.e., water supply rate is fixed at 30cf/s and the infrastructure declines by 25% every round. In the latter 10 rounds, however, each group faced one of the four experimental treatments that represent different kinds of environmental uncertainty. Note that, in round 11, the infrastructure efficiency is re-initialized to 75%. The first two treatments relate to uncertainty in the rate of infrastructure decline (Figure 4.4 A). In the *infrastructure high variability* (I-HV) treatment, the decline rate fluctuates between 10% and 80% with the mean of 25%. In the *infrastructure low variability* (I-LV) treatment, the decline rate fluctuates between 15% and 35% with the same mean of 25%. A high decline rate (e.g., 80%) represents extreme flashfloods that destroy the irrigation infrastructure. The latter two treatments relate to uncertainty in the rate of water supply feeding the infrastructure (Figure 4.4 B). In the *water supply high variability treatment* (W-HV), the supply rate varies between 20cf/s and 40cf/s. This variability is reduced to the range of 25cf/s~35cf/s under the *water supply low variability* (W-LV) treatment. The number of groups that played each treatment is 5 groups for I-LV, 6 groups for I-HV, 5 groups for W-LV, and 5 groups for W-HV treatments.

The presence of environmental uncertainty in the latter 10 rounds means that groups need to dynamically adjust their decisions to maintain their performance. Which conditions differentiate the groups that adapt successfully and those that fail to do so? We hypothesize that a group's *prior exposure* to different configurations of learning-by-doing and supporting conditions may be causally associated with how well the group adapts under environmental uncertainty. Such prior exposure may influence the level of adaptive capacity that a group develops. This paper examines potential causal linkages between configurations of learning-by-doing and supporting conditions seen in the stable rounds and the robustness of group performance in the unstable rounds.

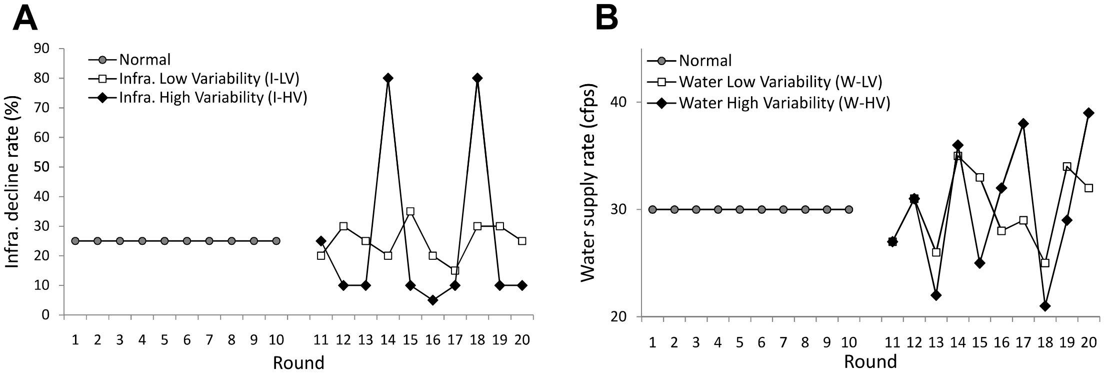


Figure 4.4. Four types of environmental uncertainty are introduced in the irrigation experiment. Panel A shows high and low variability in infrastructure decline rate. Panel B shows high and low variability in water supply rate.

4.2.2. Outcomes

We considered two outcome variables: group performance under environmental certainty and the robustness of group performance under environmental uncertainty (Table 4.1). In the stable rounds, a group's token earnings from water harvest depends heavily on the infrastructure efficiency, which in turn depends on the level of collective action achieved among participants. Thus, a group's total earnings from water harvest in an interval of rounds is an indicator for group performance (Pérez et al. 2013). We set the group earnings from water harvest in rounds 6 to 10 as our measure of group performance under environmental certainty. Earlier rounds (rounds 1 to 5) are excluded because group participants typically take a few early rounds to stabilize their behavior. Hence, group earnings from water harvest in rounds 6 to 10 is a more reliable indicator of group performance. While the lack of water harvest in rounds 1 to 5 may be of a transient nature, the deficiency of water harvest in rounds 6 to 10 is more definitive sign of poor group performance.

The robustness of group performance under environmental uncertainty is measured by comparing the group earnings from water harvest in rounds 11 to 15 (rounds with uncertainty) to that in rounds 6 to 10 (rounds with certainty). The comparison is made by deriving the ratio of group earnings from water harvest in the unstable rounds to that in the stable rounds. The ratio values around 1.0 indicate little or no change in group performance despite the uncertainty treatment (thus, a sign of robustness to the fluctuating conditions). The ratio values considerably below 1.0 signify a large drop in group performance in times of uncertainty (thus, a sign of fragility to the uncertainty). Note that groups that performed poorly in the stable rounds but performed better or similarly in the unstable rounds will likely have a ratio value near or above 1.0. Because such ratio values are misleading, we excluded the groups that performed poorly in round 6 to 10 in our analysis for robustness. See APPENDIX D for more details on how these two outcome variables are measured.

4.2.3. Causal conditions

We considered six potential causal conditions: type of learning-by-doing (inner-loop and outer-loop learning), user participation in decision-making process, knowledge-sharing, monitoring and reflection, and group coordination (Table 4.1). We analyzed both the content of group discussion and the actual decisions of group participants to evaluate the six conditions.

The occurrence of learning-by-doing may be demonstrated when participants revise their group strategies through social interactions. Of course, a change in group strategy does not necessarily mean that learning has occurred. Conversely, continuation of a group strategy does not necessarily mean that learning has not occurred. But given that learning-by-doing typically revolves around the recursive process of reflecting on past outcomes and deliberating for a new management action for testing, a change in group strategy is a relatively good proxy for the occurrence of learning-by-doing.

The existence of a group strategy adhered by participants and whether there is a change in such a shared strategy is a sign of learning-by-doing in action. If the majority of participants in a group (i.e., three or more participants) follow a same rule for either the investment or water harvest decision in a given round, we assumed that a group strategy is present in that round. For example, a group strategy likely exists when three or more participants invest a same amount of tokens or extract a same amount of water based on prior agreements made through group discussions. Whenever a group strategy for either the investment or water harvest decision is revised or updated in a round to better meet an existing goal, we treated it as an occurrence of learning-by-doing through the inner-loop (APPENDIX D). For example, if the prevailing assumption shared by group participants is to share water equally, they will experiment with various water allocation and distribution strategies to approach that goal. Likewise, if the social goal is to maintain the infrastructure efficiency at the 66~70% interval, they will test various investment strategies to move toward that goal.

Similarly, an occurrence of outer-loop learning may be detected in a given round when a group strategy for either the investment or water harvest decision is revised to meet a new goal or assumption (see APPENDIX D for the different types of social goals we identified). For example, if the content of group discussion reveals that participants share an updated assumption that 66% infrastructure efficiency is better than 81% efficiency and their subsequent decisions show they indeed switched their investment decisions to reach that new goal, it is highly likely that an outer-loop learning has occurred.

We aggregated these round-level occurrences of learning types through rounds 1 to 10 and the last practice round (see APPENDIX D). These aggregated results represent a group's exposure to inner- and outer-loop learning-by doing *prior* to environmental uncertainty. The last practice round is included because decision-making and learning frequently occur in it and carry into the subsequent rounds. Hence, we included the last practice round for more accurate analysis.

User participation for decision-making is assumed to be present in a given round whenever two or more participants propose a unique group strategy during group discussion of that round (e.g., "everyone invest 5 tokens this round", "open gate for 10 seconds only"). All unique strategy proposals are counted regardless of whether or not they are followed by participants. Similarly, monitoring and reflection is assumed to be present in a given round whenever one or more participants comment about outcomes or behaviors of individuals or the whole group (e.g., "it didn't work", "that was a bad round", "E didn't invest in the last round"), raise issues with certain individuals in order to correct their behavior (e.g., "hey A, close your gate", "hey A and B, if you don't share water, I will stop investing"), or comment about a biophysical condition (e.g., "infrastructure efficiency dropped to 45%"). We also assumed that knowledge-sharing is present in a given round whenever one or more participants give some kind of supporting information, explanation, or knowledge about the action situation of or tips about the experiment (e.g., "available water supply is only 30cf/s, so it is optimal to keep 66% efficiency"). We again aggregated these round-level occurrences of user participation, knowledge-sharing, and monitoring and evaluation through rounds 1 to 10 and the last practice round to determine their overall levels prior to environmental uncertainty.

Finally, group coordination is assumed to be present in a given round whenever the majority of participants (three or more participants) follow same rules for *both* the investment and water harvest decisions. Frequent occurrences of such a tight group coordination imply a high level of collective action or social cohesion in a group. We again aggregated the round-level occurrences of group coordination to estimate its overall level prior to environmental uncertainty.

We examined in detail both the content of group discussion and the decisions and outcomes of participants to estimate the six conditions for all 21 groups. A protocol was devised to assess the conditions (see APPENDIX D). Using the protocol, two of the co-authors independently carried out coding to determine the levels of the conditions. After the coding, the two coders came together and compared their coding results to discern where the results match and mismatch. For the mismatched results, the two coders reanalyzed the raw data and discussed until a consensus was reached. Two measures of inter-coder reliability, percent agreement and Cohen's Kappa (Cohen 1960), were derived to assess the consistency of our coding work. Cohen's Kappa score is generally thought to be more robust than percent agreement because it takes into consideration the agreement occurring by chance. Percent agreement came out to be 75%. The average of the Cohen's Kappa scores for the six conditions came out to be 59%. This score is on the borderline between being 'moderate' and 'substantial agreement' (Landis and Koch 1977) or falls in the range for 'fair to good' (Fleiss 1981).

Table 4.1. Definitions of the outcome variables and the causal conditions related to adaptability in the irrigation experiment. See APPENDIX D for more details.

Variables	Definitions
Outcomes:	
Group performance	Level of tokens earned by a group from harvesting water from the irrigation system in rounds 6 to 10 (rounds with the normal or stable conditions). This measure is derived by calibrating total number of tokens earned. The calibrated measure has a continuous scale of 0–1.0 (clearly low performance = 0, clearly high performance = 1.0).
Robustness of group performance	Level of continuity in the performance (see above) under environmental variability. This measure is derived by calculating the ratio of group earnings from water harvest in rounds 11 to 15(unstable rounds) to that in rounds 6 to 10 (stable rounds). The resulting measure is then calibrated to have a continuous scale of 0–1.0 (clearly fragile = 0, clearly resilient = 1.0).
Causal conditions:	
Inner-loop learning	How often a group changed or tested different group strategies for the investment or water harvest decision to meet an existing group goal (clearly often = 1.0, more often than not = 0.67, seldom = 0.33, clearly never = 0.0).
Outer-loop learning	How often a group changed or tested different group goals or assumptions that guide specific group strategies (clearly often = 1.0, more often than not = 0.67, seldom = 0.33, clearly never = 0.0).
User participation	Level of user participation in the decision-making processes for group strategies (clearly participatory = 1.0, more participatory than not = 0.67, less participatory than not = 0.33, clearly not participatory = 0.0).
Knowledge-sharing	Level of sharing or exchange of supporting information during group discussions (clearly present = 1.0, more present than not = 0.67, seldom present = 0.33, clearly absent = 0.0).
Group coordination	Level of participant coordination for group strategy in both the infrastructure investment and water harvest decisions (clearly present = 1.0, more present than not = 0.67, seldom present = 0.33, clearly absent

	= 0.0).
Monitoring and reflection	Level of monitoring and evaluation regarding (1) group- and individual-level outcomes and behaviors, (2) condition of biophysical components, or (3) correcting of opportunistic behaviors (clearly present = 1.0, more present than not = 0.67, seldom present = 0.33, clearly absent = 0.0).

4.2.4. Analytical approach

We used fuzzy-set qualitative comparative analysis (fsQCA) to identify possible configurations of the six conditions causally linked to the two outcome variables. Given the medium-N size (21 groups) of our sample data and our goal of identifying multiple causal configurations, we judged that fsQCA is the best analytical method available to us. fsQCA, which is based on Boolean algebra, treats an empirical case as a logical configuration of set-memberships to different conditions and outcomes (Ragin 1987, 2000). fsQCA allows researchers to identify all possible configurations of conditions that may be causally associated with the outcome of interest (Pérez et al. 2013, Basurto 2013). The set-theoretic assumption allows researchers to establish the conditions of necessity and sufficiency (Ragin 2008). A condition is necessary but not sufficient if it appears in all configurations tied to an outcome. A condition is sufficient but not necessary if its presence is associated with an outcome in certain configurations but is not the only condition with that association (i.e., there is another condition associated with that outcome). A condition is both necessary and sufficient if it is tied to an outcome and is the only condition with that linkage. For more details on the method, see Ragin (2000, 2008). Poteete et al.(2010), Basurto (2013), and Pérez et al. (2013) also provide the methodological overview or exemplary applications of the method to the study of SES.

We conducted fsQCA using a software program called fs/QCA, a widely-used tool for QCA developed by Charles Ragin and his colleagues. This software is freely available for download and use for research purposes. Visit www.compasss.org for more information about and to download fs/QCA.

We conducted fsQCA through two stages. First, all configurations of the conditions were tested for their potential causal linkage to group performance under environmental certainty. We used all of the 21 groups in this analysis. The results show which conditions are necessary, sufficient, or both for the outcome. In the second stage, we sought to identify possible configurations that may be causally linked to the robustness of group performance under environmental uncertainty. We dropped two groups (group 5 and 12) from the second analysis because they performed poorly in rounds 6 to 10. Comparison of group performance between rounds 11 to 15 and rounds 6 to 10 is not meaningful for these two groups.

We used two subsets of the remaining 19 groups for the second analysis: the sample containing all of the 19 groups and the sample containing the groups that faced the high variability treatments only (i.e., the groups that faced I-HV and W-HV treatments). Applying all of the 19 groups allows us to explore potential causal configurations linked to more general coping capacity, irrespective of the differences in the degree of environmental uncertainty. This mixing of groups with different treatments, however, may be problematic because more decline in performance may be explained by differences in the level of variability in the treatments rather than by the differences in the causal configurations. That is, groups that faced the high variability treatments likely experienced more drop in performance than those that faced the low variability treatments. Hence, we also did the second analysis using only the groups that faced the high variability treatments (I-HV and W-HV). If fsQCA shows a consistent pattern for both datasets, we can have more confidence in the results obtained.

4.3. Results

4.3.1. Trends in group performance and robustness

Figure 4.5 shows change in group performance between rounds 6 to 10 and rounds 11 to 15 for all 21 groups. In rounds 6 to 10, the mean and the median group earnings from water harvest are 249 and 268, respectively, with the minimum of 58 and the maximum of 301. Among 21 groups, 16 groups earned at least 250 tokens in the stable rounds. Hence, most of the groups performed similarly in the stable rounds. It can be seen from Figure 4.5 that groups 5 and 12 failed to perform adequately in the stable rounds. Barring these two groups, the mean and the median percentage change in group earnings between the stable and the unstable round intervals came out to be -18% and -14%, respectively, i.e., group performance generally decreased under uncertainty. The largest drop in percentage is -64%. The most positive change is +6%, i.e., one group actually increased its performance by 6% under environmental uncertainty. Figure 4.5 also visually reveals that groups that faced the high variability treatments (I-HV and W-HV) more consistently experienced decline in group performance under environmental variability. The average percentage changes in group performance with the I-HV, I-LV, W-HV, and W-LV treatments are -24%, +1%, -28%, and -2%, respectively. This pattern is expected because high variability treatments naturally pose more challenges and potential for surprise to the affected groups.

We also did cross-table comparisons between the six causal conditions and the two outcome variables. Table 4.2 shows that "monitoring and reflection" condition appears in all groups regardless of the outcome measure used. This suggests that "monitoring and reflection" is a necessary condition for both performance and robustness. Further, it can be seen that "outer-loop learning" appears in all of the groups that showed robust group performance when both the high and low variability treatments are considered. 14 out of 19 groups have set-membership to robust outcome, and they all contain that condition in their logical configurations. The same pattern occurs when only the high variability treatment groups are considered. The condition "outer-loop learning" is present in the logical configurations of the seven groups that are robust.

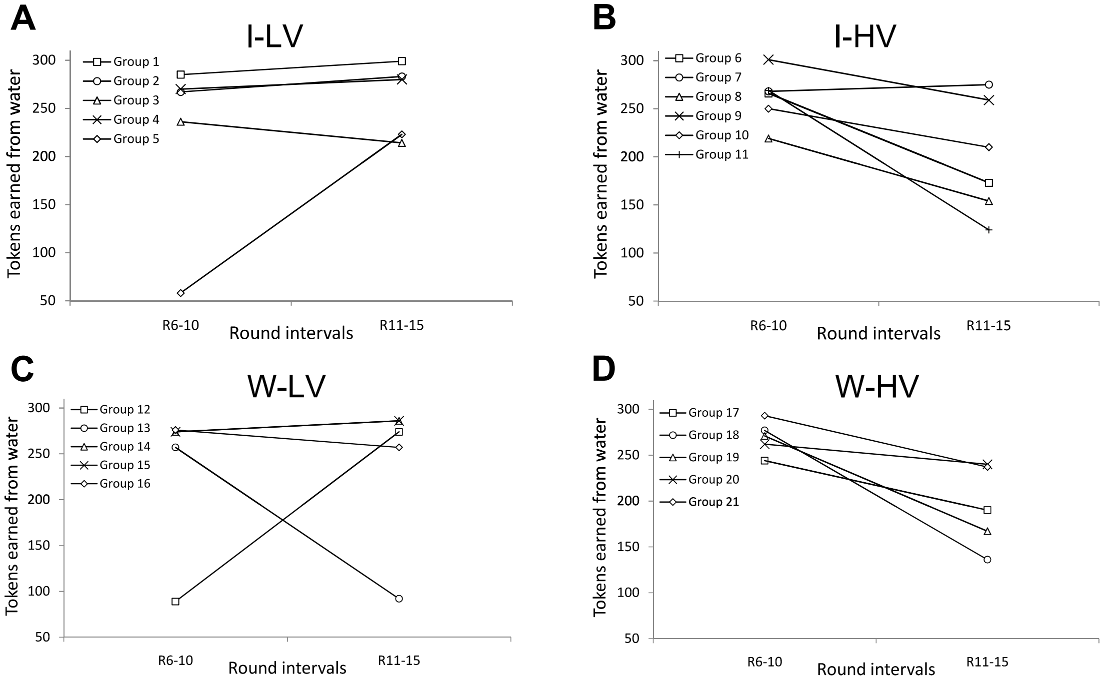


Figure 4.5. Trends in group performance and robustness in the irrigation experiment. Panels A and B show change in group performance between rounds 6 to 10 and rounds 11 to 15 for the infrastructure low variability (I-LV) and the infrastructure high variability (I-HV) treatment groups, respectively. Panels C and D show change in group performance between rounds 6 to 10 and rounds 11 to 15 for the water supply low variability (W-LV) and the water supply high variability (W-HV) treatment groups, respectively. Note that groups 5 and 12 performed poorly in rounds 6 to 10.

Table 4.2. Cross-table comparison between the causal conditions and the outcome variables of the irrigation experiment.

Conditions	Levels	Performance (N=21)		Robustness† (N=19)		Robustness‡ (N=11)	
		[0, 0.5)	(0.5, 1]	[0, 0.5)	(0.5, 1]	[0, 0.5)	(0.5, 1]
Inner-loop learning	0	2	1	1	0	0	0
	0.33	0	5	3	2	3	2
	0.67	0	10	1	9	1	4
	1.0	0	3	0	3	0	1
Outer-loop learning	0	1	2	2	0	1	0
	0.33	1	1	1	0	1	0
	0.67	0	10	2	8	2	4
	1.0	0	6	0	6	0	3
User participation	0	0	0	0	0	0	0
	0.33	1	5	2	3	2	1
	0.67	1	9	3	6	2	4
	1.0	0	5	0	5	0	2
Knowledge-	0	0	0	0	0	0	0

sharing	0.33	1	9	3	6	2	3
	0.67	1	9	2	7	2	3
	1.0	0	1	0	1	0	1
Group coordination	0	2	1	1	0	0	0
	0.33	0	6	3	3	3	1
	0.67	0	11	1	10	1	5
	1.0	0	1	0	1	0	1
Monitoring & reflection	0	0	0	0	0	0	0
	0.33	0	0	0	0	0	0
	0.67	1	14	5	9	4	4
	1.0	1	5	0	5	0	3

†Two groups are excluded (groups 5 and 12). Both the high and low variability treatment groups are included.

‡Only the high variability treatment groups (I-HV and W-HV) are included.

4.3.2. Causal configurations for performance

The results of fsQCA show two potential causal configurations linked to group performance under environmental certainty (Table 4.3). These are (1) "group coordination" combined with "user participation" and "monitoring and reflection" and (2) "inner-loop learning" combined with "outer-loop learning" and "monitoring and reflection." As hinted by the cross-table comparison, "monitoring and reflection" appears in both causal configurations, and is thus a necessary condition for group performance. The first configuration signifies that if group participants actively partake in decision-making and adhere to shared group strategies while regularly evaluating past outcomes, they can achieve good performance under environmental certainty (even without active learning-by-doing). The second configuration implies the importance of learning-by-doing: groups that actively engage in both inner- and outer-loop learning via constant evaluations of past rounds can succeed in achieving good performance. See APPENDIX C for more details on the outputs of fsQCA.

4.3.3. Causal configurations for robustness

Our fsQCA for the robustness of group performance reveals two potential causal configurations when both the high and low variability treatment groups are considered: (1) "inner-loop learning" combined with "outer-loop learning" and "monitoring and reflection" and (2) "group coordination" combined with " outer-loop learning ", "user participation", and "monitoring and reflection" (Table 4.3). The same analysis based on the groups that faced only the high variability treatments shows three potential causal configurations: (1) "group coordination" combined with "outer-loop learning", "user participation", and "monitoring and reflection", (2) "inner-loop learning" combined with "outer-loop learning", "user participation", "knowledge-sharing", and "monitoring and reflection", and (3) "inner-loop learning" combined with "outer-loop learning", "knowledge-sharing", "group coordination", and "monitoring and reflection." As expected, "monitoring and reflection" appears in all of the configurations linked to robustness. What we find more interesting is that all of the configurations linked to robustness now includes "outer-loop learning". This regularity suggests that learning-by-doing through the outer-loop is a necessary condition for robust group performance under environmental uncertainty. See APPENDIX C for more details on the fuzzy-set truth table construction and the consistency and coverage scores of the logical configurations we found.

Table 4.3. Comparison of logical configurations linked to group performance under environmental certainty and to the robustness of group performance under environmental uncertainty. See APPENDIX C 오류! 참조 원본을 찾을 수 없습니다. for more details on the outputs of fsQCA.

Performance	Robustness	
(N=21)	(N=19) Both high and low variability	(N=11) High variability only
Three configurations:	Two configurations:	Three configurations
Outer-loop learning AND Inner-loop learning AND Monitoring & reflection	Outer-loop learning AND Inner-loop learning AND Monitoring & reflection	Outer-loop learning AND User participation AND Group coordination AND Monitoring & reflection
OR	OR	OR
User participation AND Group coordination AND Monitoring & reflection	Outer-loop learning AND User participation AND Group coordination AND Monitoring & reflection	Outer-loop learning AND Inner-loop learning AND User participation AND Knowledge AND Monitoring & reflection
		OR
		Outer-loop learning AND Inner-loop learning AND Knowledge AND Group coordination AND Monitoring & reflection

4.4. Discussion and conclusion

We began this paper by highlighting the centrality of learning-by-doing for dealing with uncertainty and complexity of SES management under global change. A long-held assumption among SES scholars has been that a structured cycle of exploratory management actions, sensing and evaluation of outcomes, and adjusting next actions based on learning is crucial for SES adaptability. However, after three decades of research on adaptive management, the question of what type of learning-by-doing is most effective and under what conditions still remains largely unanswered. To help address that research gap, we turned to a laboratory behavioral experiment in which human-subjects face a decision problem on collective management of an irrigation system under environmental uncertainty. We analyzed the experimental data to measure two outcome variables (group performance under environmental certainty and the robustness of group performance under environmental uncertainty) and six potential causal conditions associated with adaptive management during the stable rounds (inner- and outer-loop learning , user participation, knowledge-sharing, monitoring and reflection, and group coordination). Our objective was to find potential causal linkages between different configurations of the six conditions seen in the stable rounds and the two outcome variables.

Using fsQCA, we found the following causal configurations for group performance under environmental certainty: (1) "group coordination" combined with "user participation" and "monitoring and reflection" and (2) "inner-loop learning" combined with "outer-loop learning" and "monitoring and reflection." Two interesting points emerge: monitoring and reflection is a necessary condition for group performance, and one configuration involves active learning-by-doing while the other is based on tight group coordination and user participation.

We also found multiple causal configurations linked to robustness. When we included all groups in the analysis, robust groups are characterized by two logical configurations: (1) "inner-loop learning" combined with "outer-loop learning" and "monitoring and reflection" and (2) "group coordination" combined with "outer-loop learning", "user participation", and "monitoring and reflection." When we considered only groups that faced the high-variability treatments, three causal configurations are found to be linked to robustness : (1) "group coordination" combined with "outer-loop learning", "user participation", and "monitoring and reflection", (2) "inner-loop learning" combined with "outer-loop learning", "user participation", "knowledge-sharing", and "monitoring and reflection", and (3) "inner-loop learning" combined with "outer-loop learning", "knowledge-sharing", "group coordination", and "monitoring and reflection". What we find interesting is that all logical configurations linked to the robustness of performance now contain "outer-loop learning" in addition to "monitoring and reflection". This implies that "outer-loop learning" is a necessary condition for robustness under environmental uncertainty.

Based on the results, we conjecture that that active explorative updating of underlying assumptions or social goals may be crucial for building SES adaptive capacity. When environmental conditions are stable, social groups may still be able to guide their SES to perform well without active learning-by-doing—as long as they are able to tightly coordinate for group strategies with active monitoring and reflection and user participation, they can still succeed. This may occur, for example, in a social group that settles early on shared goals and strategies and adheres to them by relying on constant reflection of outcomes and user participation. Updating of social goals and strategies may be rare in such a social group. However, as suggested by our results, such a group may be unable to adapt opportunely in times of environmental uncertainty. Because of the lack of experience with active learning-by-doing (in particular, outer-loop learning), such a group may not have developed enough flexibility or adaptive capacity to dynamically adjust their goals or strategies.

To reiterate, groups that were able to maintain performance under environmental uncertainty shared one prior experience in common—they have often updated assumptions or goals that underlie their specific group strategies. That is, these groups not only coordinated to adapt their actions to better meet existing goals, but they also often ventured and revised the goals themselves. Such experience may have helped the exposed groups to build adaptive capacity required for dealing with environmental uncertainty. We argue that this empirical regularity is concordant with the notion of transformability in the resilience literature. Transformability, defined as the capacity to change system structure and identity and patterns of interactions (Walker et al. 2004, Folke et al. 2010), likely requires change in underlying assumptions or goals shared by social actors. Navigating SES through change and uncertainty often forces transformative capacity on the actors involved (Olsson et al. 2004, Scheffer and Westley 2007, Folke et al. 2010). Social groups that have not built transformative capacity through frequent outer-loop learning may be unable to break away from their conventional ways of thinking or goals in times of change and surprises. They may be unable to seize the window of opportunity to transform because of their lack of exposure to the outer-loop process.

A prime example of a group that actively engaged in outer-loop learning is group 7. This group faced the high variability treatment in infrastructure decline, but still was able to performed well under both certain and uncertain conditions. The experimental data suggest that the group participants quickly tested the shared goals of maintaining the infrastructure near 100% efficiency and of equal sharing of water. In the subsequent rounds, they revised their goals: maintain the infrastructure at a moderate level (somewhere around 81% efficiency) and use water equally and efficiently (everyone harvest water equally and player E always leave his or her gate open to prevent water wastage). Such experience may have helped them to build capacity to cope with environmental uncertainty in the latter rounds. This capacity was indeed demonstrated because the group participants later anticipated that a catastrophic infrastructure decline might be on way, and again revised their investment goal to 100% infrastructure efficiency. They reasoned that 100% efficiency would create more buffer to counter a potentially large decline in the infrastructure efficiency. This anticipatory thinking enabled the group to stay fairly robust through the unstable rounds.

Groups 6, 11, and 13 are examples of groups that were able to perform well without active learning under certainty but failed to achieve the same feat under uncertainty. The experimental data show that these groups experienced little or no outer-loop learning during the stable rounds. They relied primarily on group coordination, user participation, monitoring and reflection, and/or inner-loop management learning to get through the stable rounds relatively well. However, these groups failed to maintain group performance under uncertainty because of their inability to adjust their group strategies. Their lack of experience with outer-loop learning may have caused this rigidity.

The causal configurations we identified (Table 4.3) also suggest that there may exist some *substitutability* relationship between different causal conditions. The causal configurations for robustness when both the high and low variability treatments are considered include (1) "inner-loop learning" combined with "outer-loop learning" and "monitoring and reflection" and (2) "group coordination" combined with "outer-loop learning", "user participation", and "monitoring and reflection." A comparison of these two configurations might suggest that the combination of "group coordination" and "user participation" may be equivalent or substitutable to "inner-loop learning." This potential substitutability do make some sense: groups in which users actively participate in decision-making process and tightly coordinate for group strategies will likely try different strategies proposed by various group members (which is equivalent to inner-loop learning). The causal configurations for robustness when only the high variability treatments are considered (Table 4.3) also suggest that "group coordination" and "user participation" may be equivalent or substitutable. This potential connection also makes some sense: presence of group coordination likely means that everyone is buying into the management system and is thus probably more motivated to contribute to the decision-making process.

Finally, our research findings may have some implications to one related area of research. Recent years have witnessed the growing applications of the resilience paradigm to the management of critical infrastructure systems under uncertainty (e.g., Fiksel 2003, Hollnagel et al. 2006, McDaniels et al. 2008, Park et al. 2011, Chang et al. 2014, Linkov et al. 2014). One of the key messages that have emerged from this line of research is that a recursive process involving sensing of outcomes, anticipation, adaptation, and innovation and learning is crucial for adaptive management of complex infrastructure systems (Klein 2003, Gunderson 2010, Zhou 2010, Park et al. 2013). Because irrigation systems are a highly-engineered form of SES in which infrastructure is coupled to natural and social systems, our findings about the outer-loop learning may be also applicable to the adaptive management of critical infrastructure systems.

To conclude, our results show that prior exposure to active outer-loop learning is a necessary condition for successful management of SES under environmental uncertainty. SES characterized by rigidity of social goals or underlying assumptions may be particularly more vulnerable when they are subjected to environmental shocks. We suggest that resilience practitioners and policy-makers interested in improving general resilience must consider fostering the culture of outer-loop learning in their SES. We also suggest some directions for the future studies. Our research relied on the experimental data from the undergraduate students of a U.S. university. Future studies may consider conducting a field experiment participated by real resource users and managers to incorporate more realistic contexts into the analysis. Power asymmetry among social actors may also be an important causal condition related to performance and robustness (Biggs et al. 2012). Future studies may devise an experiment with one additional experimental treatment: groups with significant power asymmetry among human-subjects and those with zero asymmetry in power.

5. CONCLUSION

5.1. Summary of the research findings

Social-ecological systems (SES) are faced with two undeniable trends in the Anthropocene (Crutzen and Stoermer 2000), the era of domineering human influence on the Earth's ecosystem processes. On the one hand, SES have become increasingly populated with hard and soft human-made infrastructures that affect how humans benefit from and interact with the environment (Anderies et al. 2004, Anderies 2014a). On the other hand, global change issues have increased the complexity and uncertainty present in the dynamic elements of SES (Dietz et al. 2003, Polasky et al. 2011). A key challenge for sustainability is then how we can maintain the capacity of infrastructure-dependent SES to perform their intended functions in the face of change and surprise.

To help address this broader question, I tackled the following research questions throughout the thesis. First, how the designed features of physical or social infrastructure affect the incentives that users face in collective action problems associated with infrastructure maintenance and resource appropriation, and how such effects, in turn, influence the long-term dynamics of SES under global change? Second, in the face of uncertainty generated by global change, how can we guide adaptive management of infrastructure-dependent SES for more robustness? Below, I summarize my research findings.

In Chapter 1, I used a stylized dynamic model of an irrigation system to examine how some of the designed features of irrigation infrastructure affect the long-term dynamics of social norm and system performance in the face of collective action problems and an external economic shock. The model results suggest that change in two designed features—asymmetric access to water and threshold of infrastructure maintenance—can cause regime shifts as well as a considerable alteration in robustness characteristics. When the model system's canal layout induces asymmetric access to water among farmers, there emerged a regime of economic inequality between upstream and downstream users. This supports the empirical regularity observed in field studies (e.g., Bardhan and Dayton-Johnson 2002). I also observed that the regimes of economic inequality, system collapse, and sustainability emerged, expanded, or shrunk as the threshold of infrastructure maintenance was varied.

In Chapter 2, I analyzed an existing case study of 89 self-governed forest commons (Kang 2001) to explore how connectedness among social units (a kind of social infrastructure) influenced the post-failure transformations of the commons under economic globalization. In particular, I focused on the effects of two structural properties of the social connectedness that had developed in each commons system as it adapted to local conditions: the number of horizontal links (the number of participating villages in a system) for joint collective action and the degree of cross-system links (the ratio of participating villages that are also part of another commons system). By conducting secondary analysis on Kang (2001)'s original data, I tried to uncover how the two structural properties affected the trajectories of transformation undergone by the systems under economic globalization. I found some evidence that while the degree of cross-system links is associated with desirable forms of transformation (e.g., maintenance of the forest commons, conversion to alternative social goods), the number of horizontal links is associated with undesirable forms of transformation (e.g., sell the forest commons and divide the proceeds from the sale among households).

In Chapter 3, I used an existing laboratory behavioral experiment (Anderies et al. 2013a) to examine the question of how we can guide adaptive management of infrastructure-dependent SES for more robustness under uncertainty. In the experiment, human-subjects tackled a decision problem on collective management of an irrigation system under environmental uncertainty. I analyzed the contents of group communication and the decisions and outcomes of individuals to find configurations of conditions related to adaptability (types of learning-by-doing and supporting conditions such as user participation, knowledge-sharing, monitoring and reflection, etc.) that are causally linked to the robustness of group performance under environmental uncertainty. The results show that two conditions are necessary for robustness: active adjusting of assumptions or goals shared by human subjects and active monitoring and reflection of outcomes in previous rounds.

5.2. Synthesis of the research findings

I now synthesize the research findings of the thesis. First, I was able to observe a pattern of robustness-fragility tradeoffs under different designed conditions of infrastructure in the SES I studied. In Chapter 2, it was found that lower thresholds of infrastructure maintenance make the system more robust to system collapse, but in so doing inadvertently make the system more fragile to economic inequality (when combined with asymmetric access to water). It was also shown that the system output of infrastructure efficiency is more sensitive to the effects of wage shocks under lower maintenance thresholds. Conversely, higher thresholds of infrastructure maintenance make the system more robust to economic inequality, but at the same time cause the system to be more fragile to system collapse. Similarly, in Chapter 3, evidence suggests that a structural aspect of social connectedness that had helped villages to be better adapted to local conditions inadvertently caused their forest commons to be more fragile to undesirable forms of transformation in the current era of economic globalization. Horizontal links that were created among villages for beneficial purposes (i.e., economize the cost of managing large-scale commons) created fragility to undesirable forms of transformation because of higher transaction costs associated with maintaining those links. These fragilities were exposed when the economic salience of forest resources declined as a result of economic globalization.

These patterns of shifting fragilities are concordant with the fundamental property of robustness-fragility tradeoffs which is known to be present in all feedback systems (Csete and Doyle 2002). This property suggests that a system feature that contributes to controlling the sensitivity of a system output to a particular disturbance necessarily leads to hidden system fragilities to some unexposed disturbances. Because the SES that I examined in this thesis contain either hard or soft human-made infrastructures that are created for a purpose, it is unsurprising that hidden fragilities of these systems were realized when they were exposed to novel conditions (see Janssen and Anderies 2007, Janssen et al. 2007 for other examples).

Second, the robust-yet-fragile nature of SES likely means that design for robustness is insufficient for sustaining complex SES in the face of uncertainty. The risk-based engineering approach, which is a conventional method for attaining robustness, typically involves the following tasks: identify all possible threats and their probabilities and deploy some designed solutions to preemptively deal with the identified threats (Park et al. 2013, Linkov et al. 2014). However, given that global change issues generate irreducible amount of uncertainty in what kinds of shocks will be faced by SES in the long run, it is impossible for the risk-based approach to ensure robustness all the time. Further, any design fixes that we introduce to deal with a particular kind of shock will likely create hidden fragilities that will be materialized only when unforeseen shocks arrive at a later time. This means that the risk-based engineering approach of SES must be complemented by another approach that helps SES to build adaptability to deal with all types of shocks in the long-run (Park et al. 2013).

But how can we build such adaptability that gives rise to SES resilience or robustness? What kind of engineering or management approach is required to achieve it? To date, multiple heuristics or approaches have been proposed to implement adaptability in practice: adaptive management (Walters and Holling 1990), adaptive co-management (Armitage et al. 2009), robustness of SES approach (Anderies et al. 2013b), and resilience engineering of built systems for safety management (Hollnagel 2014). These approaches all emphasize one condition in common—centrality of learning for achieving adaptability. For example, Anderies et al. (2013b) suggest that social actors must constantly monitor and learn about their SES and changing conditions and then dynamically modify their system by choosing which disturbances they want to be robust against and which fragilities they can live with at a particular point in time. Likewise, adaptive management highlights that learning is needed because knowledge about SES is often incomplete and change and surprise are inevitable in coupled social and ecological processes. It suggests that management experiments facilitate actors to learn about the consequences of exploratory management actions and to update existing strategies and assumptions, so that SES can persist through uncertainty. In addition to learning, these approaches also highlight the importance of several other conditions for achieving adaptability: participatory process, knowledge-generation, and monitoring and reflection for adaptive management or co-management (Armitage et al. 2009, Plummer et al. 2012, Fabricius and Cundill 2014), diversity and redundancy of system functions and modularity of system structure for robustness (Anderies and Janssen 2011), and the system capacity to respond to shocks, monitoring of system performance and environmental conditions, and anticipation for proactive adaptation for resilience engineering (Hollnagel 2014).

However, the evidence in support of these approaches does not indicate which specific combinations of the above conditions may be causally linked to enhanced adaptability (Biggs et al. 2012, Fabricius and Cundill 2014, Hollnagel 2014). Do all of such conditions must be present? Or, are certain combinations of them more crucial than others? In Chapter 4, I focused on a subset of the conditions thought to be related to adaptability (user participation, knowledge-sharing, monitoring and reflection, level of group coordination, and different types of learning-by-doing) and found that two conditions may be necessary for achieving enhanced adaptability: active monitoring and reflection of past outcomes and learning-by-doing through outer-loop (frequent updating of underlying assumptions or goals). To sum it up, the risk-based engineering or management of SES is insufficient for ensuring sustainability under global change because of the robust-yet-fragile nature of SES. To overcome this problem, we need to improve system adaptability by investing in the social capacity to carry out constant monitoring and reflection of past outcomes and in the social capacity to flexibly adjust underlying goals or assumptions.

Third, design criteria for robust SES must consider the potential for robustness-fragility tradeoffs associated with different design choices. The notion of robust-yet-fragile nature of designed systems is obvious for physically built systems such as buildings, bridges, and jet airplanes. Engineers working with these systems routinely conduct risk analyses and simulations to explicitly consider how tradeoffs in system fragilities occur under different design choices. These considerations for tradeoffs allow engineers to build systems that remain robust in most of the circumstances. The same considerations for tradeoffs, however, are less obvious and less appreciated for partly-designed, complex SES that operate on much slower time scale and broader spatial scale, such as irrigation, forestry, and urban water systems. My thesis and the pioneering works by Anderies et al. (2004) and Janssen et al. (2007) make a strong point in this regard—that most SES are infrastructure-dependent and thus exhibit the fundamental property of robustness-fragility tradeoffs.

Further, design criteria for robust SES must consider how designed aspects affect the social capacity to organize and maintain collective action. This capacity is, in turn, probably tied to enhanced system adaptability. I argue that without the ability to organize and maintain collective action, the component parts of adaptability such as learning and anticipation will likely not function. Hence, to improve adaptability, designers of physical and social infrastructures must ensure that their design choices do not adversely affect the structure of incentives that users face in collective action situations. What is the nature of this structure of incentives? Which specific structural variables or micro-situational variables should we consider when making design choices? **A useful starting ground is considering how designed aspects of infrastructure may affect some of the structural variables or micro-situational variables that are thought to be tied to collective action or durability of institutions** (Agrawal 2002, Ostrom 2005b, Poteete et al. 2010). These variables include, for example, shape of production function, heterogeneity among participants, interdependency among participants, number of participants, ease of communication, information about past outcomes, freedom to enter or exit, and ease of monitoring and sanctioning, among others. For example, the design of production infrastructure can influence the structural variables of production function shape and interdependency among users. Likewise, the design of distribution infrastructure can influence the structural variables of heterogeneity, interdependency, and ease of monitoring and sanction among users. The design of social infrastructure (such as organizational form or social institutions) may also influence the structural variables of ease of communication, information about past outcomes, and freedom to enter or exit, among others. Because these structural variables influence the likelihood of individuals to solve collective action problems (and thus ultimately system-level adaptability), engineers and policymakers responsible for designing physical and social infrastructures must carefully consider how their choices subtly influence these variables.

Finally, based on the SES I studied in this thesis, I highlight some designed aspects of physical and social infrastructure that I found to be crucial for collective action and SES adaptability.

- Design choices for production infrastructure must foster an adequate level of interdependency among different user groups for achieving a productive outcome. Such interdependency is especially important when multiple user groups are heterogeneous in their capacity to compete for resources because of the nature of distribution infrastructure. If the interdependency is too strong, a system may become fragile to system collapse from opportunistic behavior. If the interdependency is too weak, a system may become fragile to economic inequality.
- Design choices for social infrastructure must foster smaller user group size and more connections to outside systems. Smaller group size may reduce the transaction cost of maintaining collective action in a SES. More connections to outside systems likely generate more flows of knowledge and information, which likely help SES adaptability.
- Design choices for production, distribution, or social infrastructure must facilitate monitoring and sanction, reflection of information on past outcomes, group communication, as well as group-level learning linked to active updating of underlying goals or assumptions. For example, shorter networks of distribution infrastructure facilitate monitoring and sanction, whereas long stretches of

distribution infrastructure may make the monitoring difficult. Creating a social infrastructure such as arenas for regular community meetings and participatory decision-making process may facilitate group communication and social flexibility to achieve active updating of underlying goals or assumptions.

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APPENDIX A

MATHEMATICAL BACKGROUND FOR CHAPTER 2

A.1. Dynamics of the strategies

N farming households are spread across two villages (Village 1 and Village 2) that co-manage a single irrigation system. The number of households in each village is N_1 and N_2, respectively, which satisfy $N_1 + N_2 = N$. The irrigation system is governed by the following rules. Maintenance labor to be contributed by a farmer is proportional to his or her acreage. Water allocated to a farmer is proportional to his or her acreage, but only among the water rights holders. Only farmers who contributed labor to the infrastructure prior to the planting season obtain water rights. Farmers choose between two strategies: group-conformist (*G*) and opportunist (*O*). *G*s follow and enforce the rules, and strive to maximize the total welfare of the two villages. *O*s break the rules and attempt to maximize individual net income.

Our model tracks the fraction of *G*s in Village *i* denoted by $X_i = N_i^G / N_i$. We define the total number of *G*s as $N^G = N_1^G + N_2^G$. Finally, the fraction of *O*s in Village *i* is $1 - X_i = N_i^O / N_i$. We used replicator equations below to track the fractions of the strategies in Villages 1 and 2.

$$\frac{dX_1}{dt} = X_1[\pi_1^G - \bar{\pi}_1]$$

$$\frac{dX_2}{dt} = X_2[\pi_2^G - \bar{\pi}_2]$$

Here, π_i^G is the payoff of *G* in Village *i*. The term $\bar{\pi}_i$, the average payoff of a farmer in Village *i*, is given by $\bar{\pi}_i = \pi_i^G X_i + \pi_i^O (1 - X_i)$, where π_i^O is the payoff of *O* in the same village.

To explore the dynamics of our model system, we used *XPPAUT*, a software package specialized for studying non-linear dynamical systems. *XPPAUT* numerically derives local stability properties of equilibrium points, i.e., a set of system states (X_1, X_2) where the changes in X_1 and X_2 are zero as time is varied. Equilibrium points reveal the stable attractors of our model system.

A.2. Infrastructure efficiency

Let $I(L_m)$ be the efficiency of the shared irrigation infrastructure, where L_m is the sum of maintenance labor provided by all farmers each year, i.e., $L_m = \sum l_m$. Farmers have to maintain the infrastructure each year (canals must be cleaned of silt and debris, and water diversion structures such as weirs must be repaired) to keep the irrigation infrastructure functional. A threshold of labor is assumed for the maintenance of infrastructure, i.e., little or no water is generated until the annual maintenance labor reaches a certain threshold (see Figure A.1 and the equation below). We use a piece-wise linear function to represent this maintenance threshold. Here, I_{max} is the maximum infrastructure efficiency. The half-saturation point of labor (ψ) and half-width of the threshold slope (ϵ) determine the threshold of maintenance ($\psi - \epsilon$). When the maintenance labor is in the range of $\psi - \epsilon \leq L_m \leq \psi + \epsilon$, the efficiency increases by $I_{max} / 2\epsilon$ per unit of L_m. Below this range, the efficiency is zero. Above this range, no further efficiency is generated by adding more labor. Total irrigation water is given by $Q = I(L_m)S(t)$, where $S(t)$ is the abundance state of a renewable water resources system such as river. In this study, $S(t)$ is the main natural component of our model system and is assumed to be constant ($S(t) = S$), i.e., there is always a constant source of water from which farmers can divert water. Of course, $S(t)$ can be more elaborate and have its own dynamics (i.e., rainfall, evaporation, etc.). We chose the simplest representation ($S(t) = S$) because this allows us to focus on the effects of infrastructure design.

$$I(L_m) = \begin{cases} 0 & 0 \leq \mathrm{L_m} < \psi\text{-}\epsilon \\ \dfrac{I_{max}}{2\epsilon}(L_m - \psi + \epsilon) & \psi - \epsilon \leq \mathrm{L_m} \leq \psi + \epsilon \\ I_{max} & \psi + \epsilon < \mathrm{L_m} \leq \mathrm{L} \end{cases}$$

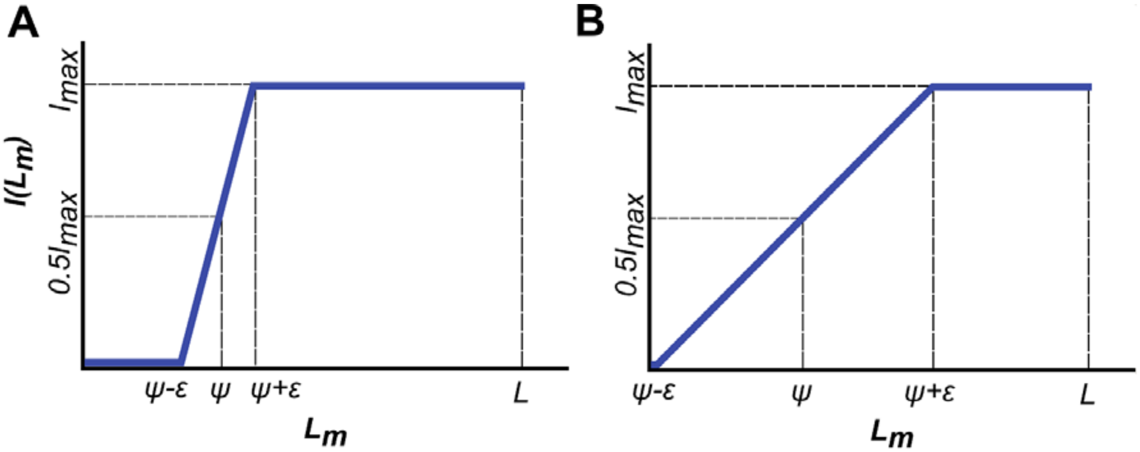

Figure A.1. Threshold and linear provision of infrastructure maintenance. Panel A shows a high-threshold infrastructure (a threshold public good). Panels B shows a low-threshold infrastructure (a linear public good).

A.3. Income

Each farmer is endowed with the same amount of available labor (l) each year. A farmer may appropriate a volume of water (q) from the system, and allocate labor among three kinds of work: farming (l_f), maintaining infrastructure (l_m), and outside employment (l_e) with wage rate w, i.e., $l = l_f + l_m + l_e$. Let $f = f(l_f, q_i, a_i)$ be a farmer's agricultural output in village *i*, which depends on the production inputs of farming labor (l_f), irrigated water (q_i), and acreage (a_i) (lowercase symbols are individual-level quantities). We specify f using a standard production function,

$f = b(l_f)^j (q_i + r_i)^k a_i^{(1-j-k)}$, where b is productivity coefficient for inputs of production, r_i is the amount of freely-available alternative water (e.g., rainfall) that a farmer receives, and j and k represent output elasticity of farming labor and irrigated water, respectively. A farmer's income from agricultural production is then given by pf, where p is price per unit of agricultural yield. In addition, the income from outside employment is given by wl_e, where wl_e is the wage rate for outside employment. A farmer total income in village *i* is then given by:

$$\pi_i = pb(l_f)^j (q_i + r_i)^k a_i^{(1-j-k)} + wl_e$$

Note that we assume each farmer is endowed with the same acreage (a_i). This assumption is restrictive because farmers would likely be heterogeneous in their acreage in most irrigation systems. Nevertheless, this assumption enables us to focus on the effects of asymmetry in distribution infrastructure. Moreover, implementing asymmetry in acreage at individual level would require a different modeling approach such as agent-based modeling. Future studies may focus on the interaction effects between asymmetries in acreage and distribution infrastructure using agent-based modeling.

Similarly, the aggregate income of the two villages is given by:

$$\Pi = pb(L_f)^j (Q + R)^k A^{(1-j-k)} + wL_e$$

where the upper case symbols represent aggregate-level quantities.

A.4. Optimal maintenance of infrastructure

We used the method of Lagrange multipliers for constrained optimization to calculate the optimal values of total maintenance labor L_m^*, farming L_f^*, and employment L_e^*, that would maximize the aggregate income (Π) of the two villages. This problem can be express as follows:

$$\max_{L_f, L_m} \Pi = pbL_f^j [I(L_m)S + R]^k A^{1-j-k} + wL_e; \text{ subject to: } L_f + L_m + L_e = L,$$

where L is the total available labor of the farmers in the two villages, i.e., $L = (N_1 + N_2)l$. We assumed that each farmer is endowed with an equal amount of labor each year (l), and N_1 and N_2 represent the number of farmers in Villages 1 and 2, respectively. Note that we can rewrite the expression for Π replacing L_e by $L - L_m - L_f$.

The optimization is performed for the three different regions of the infrastructure efficiency $I(L_m)$. In the following, we present the different optimal values of L_f, L_m, L_e, for these different regions.

- Region I: $0 \le L_m \le \psi - \epsilon$; $Q(L_m) = I(L_m)S = 0$.

Clearly, $L_m^* = 0$. This is because any maintenance labor in this region would not exceed the threshold ($\psi - \epsilon$). As a result, the optimization problem becomes:

$$\max_{L_f, L_e} \Pi_I = pbL_f^j R^k A^{1-j-k} + wL_e; \text{ subject to: } L_f + L_e = L.$$

Using the constraint, we can rewrite $\Pi_I = pbL_f^j R^k A^{1-j-k} + w(L - L_f)$. We then solve $d\Pi_1 / dL_f = 0$ to obtain the following optimal values: $L_f^* = (jpbA^{1-j-k}R^k / w)^{\frac{1}{1-j}}$, and $L_e^* = L - L_f^*$. The maximum value of the aggregate income is:

$$\Pi_{I,max} = pbA^{1-j-k}(L_f^*)^j R^k + w(L - L_f^*).$$

When the return for wage labor is zero ($w = 0$), the optimal values become: $L_m^* = L_e^* = 0$, $L_f^* = L$, and $\Pi_{I,max} = pbA^{1-j-k}L^j R^k$.

- Region II: $\psi - \epsilon < L_m \le \psi + \epsilon$; $\quad Q(L_m) = I(L_m)S = \frac{Q_{max}}{2\epsilon}(L_m - \psi + \epsilon)$, where $Q_{max} = I_{max}S$.

    The optimization problem in this region becomes:

$$\max_{L_f, L_m} \Pi_{II} = pbL_f^j \left[\frac{Q_{max}}{2\epsilon}(L_m - \psi + \epsilon) + R \right]^k A^{1-j-k} + wL_e;$$

$$\text{subject to: } L_f + L_m + L_e = L, \quad \text{and} \quad L_m \le \psi + \epsilon$$

Using the equality constraint to set $L_e = L - L_f - L_m$, we define the Lagrangian as follows:

$$\Lambda(L_f, L_m, \lambda) = pbL_f^j \left[\frac{Q_{max}}{2\epsilon}(L_m - \psi + \epsilon) + R \right]^k A^{1-j-k} + w(L - L_f - L_m) + \lambda(\psi + \epsilon - L_m),$$

where λ is the lagrange multiplier for the inequality constraint. To calculate the optimal values L_f^* and L_m^*, we solve the following set of equations:

$$\frac{\partial \Lambda}{\partial L_f} = \frac{\partial \Lambda}{\partial L_m} = \frac{\partial \Lambda}{\partial \lambda} = 0;$$

with the complementarity condition $\lambda(\psi + \epsilon - L_m) \ge 0$ and $\lambda \ge 0$ to obtain the following values.

When $\lambda = 0$ (i.e., $L_m < \psi + \epsilon$):

$$L_f^* = A\left[\frac{jpb}{w} \left(\frac{kQ_{max}}{2j\epsilon} \right)^k \right]^{\frac{1}{1-j-k}},$$

$$L_m^* = \psi - \epsilon - \frac{2\epsilon R}{Q_{max}} + \frac{2\epsilon A}{Q_{max}} \left[\frac{jpb}{w} \left(\frac{kQ_{max}}{2j\epsilon} \right)^{1-j} \right]^{\frac{1}{1-j-k}}, \text{ and}$$

$$L_e^* = L - L_f^* - L_m^*.$$

The maximum value of the aggregate income can be calculated by substituting the optimal values:

$$\Pi_{II,max} = pbA^{1-j-k}(L_f^*)^j \left[\frac{Q_{max}}{2\epsilon}(L_m^* - \psi + \epsilon) + R \right]^k + w(L - L_f^* - L_m^*) .$$

When $w = 0$, the optimal values become:

$$L_m^* = \frac{1}{j+k}\left[kL + j(\psi - \epsilon) - \frac{2j\epsilon R}{Q_{max}} \right], \quad L_f^* = L - L_m^*, \quad L_e^* = 0 \text{, and,}$$

$$\Pi_{II,max} = pbA^{1-j-k}(L - L_m^*)^j \left[\frac{Q_{max}}{2\epsilon}(L_m^* - \psi + \epsilon) + R \right]^k .$$

When $\lambda > 0$ (i.e., $L_m = \psi + \epsilon$); the optimal values will be equal to those for the region III that are presented next.

Region III: $\psi + \epsilon \le L_m \le L$; $\quad Q(L_m) = I_{max}S = Q_{max}$.

The optimal value of the maintenance labor is $L_m^* = \psi + \epsilon$. The optimization problem then becomes:

$$\max_{L_f, L_e} \Pi_I = pbL_f^j \left[Q_{max} + R \right]^k A^{1-j-k} + wL_e ; \text{ subject to: } L_f + L_e = L - \psi - \epsilon .$$

Using the constraint, the aggregate income becomes: $\Pi_{III} = pbA^{1-j-k}\left[Q_{max} + R \right]^k + w(L - L_f - \psi - \epsilon)$. We then solve for $d\Pi_{III} / dL_f = 0$ to obtain the following optimal values:

$$L_f^* = \left[\frac{jpbA^{1-j-k}(Q_{max} + R)^k}{w} \right]$$

$$L_e^* = L - \psi - \epsilon - \left[\frac{jpbA^{1-j-k}(Q_{max} + R)^k}{w} \right] \text{, and}$$

$$Pi_{III,max} = pbA^{1-j-k}(L_f^*)^j \left[Q_{max} + R \right]^k + w(L - \psi - \epsilon - L_f^*) .$$

When $w = 0$, the optimal values become: $L_m^* = \psi - \epsilon$, $L_e^* = 0$, $L_f^* = L - \psi - \epsilon$, and $\Pi_{III,max} = pbA^{1-j-k}(L - \psi - \epsilon)^j \left[Q_{max} + R \right]^k$.

A.5. Strategy payoffs under upstream-downstream asymmetry

Our model system is governed by the following rules. Maintenance labor to be contributed by a farmer is proportional to his or her acreage. Water allocated to a farmer is proportional to his or her acreage, but only among the water rights holders. Only farmers who contributed labor to the infrastructure prior to the planting season are given water rights. Farmers choose between two strategies: group-conformist (*G*) and opportunist (*O*). *G*s follow and enforce the rules, and strive to maximize the total welfare of the two villages. *O*s break the rules and attempt to maximize individual net income.

Each *G* assumes everyone will contribute to the public infrastructure and contributes their proportionate share ($1/N$) of the optimal total maintenance labor (L_m^*), attempts to take only the allocated share ($1/N^G$) of the total water (Q), and allocates labor between farming and employment to maximize the total income. *G*s also monitor for rule violations in their own Village *i* and the other village *j* ($i \neq j$), and punish violators at a cost to themselves. The cost of enforcement for a *G* increases with the frequencies of opportunists, i.e., $\left[\gamma_s\left(1-X_i\right)+\gamma_o\left(1-X_j\right)\right]$ where γ_s and γ_o represent the maximum enforcement costs for the same village and the other village, respectively.

*O*s contribute zero maintenance labor ($l_m = 0$), and thus do not hold water rights. Nevertheless, they steal as much of other farmers' water as they can within the limits set by the penalties imposed, their relative capacity for competing for water in comparison to others, and the benefits to be gained by using the outside employment options. *O*s steal an amount of water and allocate the labor saved from skipping the maintenance work to other work (either more farming or employment labor) to maximize their individual net income. The probability of being caught and punished increases with the average frequency of *G*s, i.e., $(X_i + X_j)/2$. The penalty varies by situation: it increases with the amount of water stolen (q^O), but decreases with water abundance in the system. When water is abundant, rule violations are tolerated because farmers have little incentives to concern themselves with equity issues. This effect is represented by $\delta[1-\sigma Q(L_m)/Q(L_m^*)]q^O$; where δ is the maximum penalty, $Q(L_m)/Q(L_m^*)$ is the proxy for water abundance, and $\sigma \leq 1$ is the tolerance factor. If $\sigma \approx 0$, farmers hardly tolerate water theft even if water is abundant.

The payoffs of the two strategies in Village 1 are given by the following two equations.

$$\pi_1^G = c_1(l_f^G)^j(q_1^G + r_1)^k + w\left(l_e^G\right) - \left[\gamma_s\left(1-X_1\right)+\gamma_o\left(1-X_2\right)\right]$$

$$\pi_1^O = c_1(l_f^O)^j\left(q_1^O + r_1\right)^k + w\left(l_e^O\right) - \delta\left(1-\sigma\frac{Q(L_m)}{Q(L_m^*)}\right)q_1^O\left(\frac{X_1+X_2}{2}\right)$$

Likewise, the payoffs of the two strategies in Village 2 are given by the following two equations.

$$\pi_2^G = c_2(l_f^G)^j(q_2^G + r_2)^k + w\left(l_e^G\right) - \left[\gamma_s\left(1-X_2\right)+\gamma_o\left(1-X_1\right)\right]$$

$$\pi_2^O = c_2(l_f^O)^j\left(q_2^O + r_2\right)^k + w\left(l_e^O\right) - \delta\left(1-\sigma\frac{Q(L_m)}{Q(L_m^*)}\right)q_2^O\left(\frac{X_1+X_2}{2}\right)$$

Here, $c_i = pb(a_i)^{1-j-k}$, and $Q(L_m^*) = I(L_m^*)S$ is the optimal total amount of water desired by the two villages, and $Q(L_m) = I(L_m)S$ is the total amount of water actually available in the system. The above payoff equations assume that all farmers share common knowledge on the water abundance proxy $Q(L_m)/Q(L_m^*)$. Alternative formulations could be introducing heterogeneity into this awareness among farmers and adding non-linearity to the proxy. Such formulations would likely make the system dynamics more interesting, possibly introducing additional bifurcations. Note that π_i^G could be negative if enforcement cost is larger than the combined farming and wage income. In such cases, we impose the condition that $\pi_i^G = 0$. Finally, we assume $\gamma_o > \gamma_s$ because a farmer's cost for monitoring own village should be cheaper than that for monitoring other village.

For the analysis, we used a set of default model parameter values (Table A.5). Figure A.2 A and B are phase-space representations of the overall cooperation level of the system. Figure A.2 A suggests that, in the absence of asymmetry, two regimes typically emerge for most parameters explored: all *O*s (*ALL-O*s) and all *G*s (*ALL-G*s). There is no inequality in total income between Villages 1 and 2 in these two regimes. With asymmetry, however, three regimes are possible: *ALL-O*s; a sustainable situation in which most are *G*s in Village 1, but all are *G*s in village 2 (*MOSTLY-G*s); and a decoupled situation in which the two villages stop collaborating for a common goal, i.e., *G*s dominate in Village 1 but *O*s prevail in Village 2 (*DECOUPLED*) (Figure A.2 B).

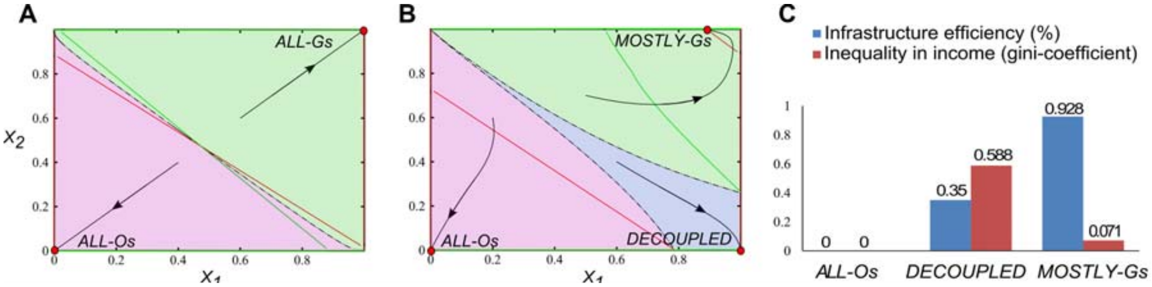

Figure A.2. Comparison of dynamics with and without upstream-downstream asymmetry. The *x* and *y* axes show the fractions of *G*s in Village 1 (X_1) and Village 2 (X_2), respectively. Red dots represent stable equilibrium points of the dynamics. Arrows represent the flows of dynamics from particular initial states. Red and green lines represent X_1 and X_2 nullclines, respectively. Panel A shows possible dynamics when asymmetry is absent. Two regimes are possible: *ALL-O*s and *ALL-G*s. Income inequality does not exist in these two regimes. Infrastructure is fully maintained at *ALL-G*s, but the system collapses at *ALL-O*s. Panel B shows possible regimes under asymmetry: *ALL-O*s (light pink area), *MOSTLY-G*s (light green area), and *DECOUPLED* (light blue area). At *ALL-O*s, the irrigation system collapses. At *MOSTLY-G*s, most farmers follow the rules, water is almost fully supplied, and some income inequality exists between the villages. At *DECOUPLED* farmers in Village 2 leave farming, and considerable inequality in total income exists between Villages 1 and 2. Panel C shows a comparison of the three regimes shown in B (model with asymmetry) in terms of infrastructure efficiency and income inequality between Villages 1 and 2. Income inequality is computed by deriving gini-coefficients of total income between Villages 1 and 2. The default parameter values are: $w = 0.2$, $\psi = 0.2$, $\epsilon = 0.125$, $I_{max} = 1$, $S = 100$, $a = 1$, $l = 1$, $N_1 = N_2 = 50$, $\gamma_s = 0.05$, $\gamma_o = 0.1$, $\delta = 1.4$, and $\sigma = 0.9$.

Figure A.2 C compares the three regimes of the asymmetric case in terms of infrastructure efficiency and inequality in total income. At *ALL-O*s, no water is supplied and everyone is equally bad off. At *MOSTLY-G*s, water is almost fully supplied and the two villages have a roughly equal total income (but the income of Village 1 is somewhat higher than that of Village 2). At *DECOUPLED*, some water is supplied but considerable income inequality exists at village-level because only farmers in Village 1 obtain irrigated water. Farmers in Village 2 leave agriculture and resort to outside employment.

In the following sub-sections, we specify the decisions of *G*s and *O*s regarding their labor allocations and the amount of water they appropriate.

- Case 1 ($L_m \ge \psi - \epsilon$)

When $L_m \ge \psi - \epsilon$, the optimal maintenance labor (L_m^*) is derived by solving the following maximization problem:

$$\max_{L_f, L_m} \Pi = pbL_f^j[I(L_m)S+R]^k A^{1-j-k} + wL_e; \text{ subject to: } L_f + L_m + L_e = L .$$

A special case occurs when $\psi + \epsilon \le \mathrm{L_m} \le \mathrm{L}$. In this situation, the optimal maintenance labor becomes $L_m^* = \psi + \epsilon$.

Without upstream-downstream asymmetry, the two villages have equal access to water. For simplicity, let us assume that *within* each village, farmers also have equal access. Here, farmers are symmetric in their capacity for competing for water because they all have equal access to water and are endowed with the same levels of available labor, technology, and skills. It follows that if all farmers are to rush and compete for water, they will face, on average, a constraint of Q/N on the amount of water they obtain. Hence, *O*s in each village harvest water and allocate labor at levels that maximize their payoff subject to the conditions $q_i^O \le Q/N$ and $l_f^O + l_e^O = l$. The total amount of water taken by *O*s in each village is $Q_i^O = q_i^O\left(1 - X_i\right)N_i$ and we define $Q^O = Q_1^O + Q_2^O$. It follows, then, that *G*s in each village obtain the amount of water given by $q_i^G = \left[Q - Q^O\right]/N^G$, which is less than what they should receive (Q/N^G).

In the setting with upstream-downstream asymmetry, water is accessed sequentially—farmers in Village 1 access water before those in Village 2. Note that the total amounts of water appropriated by *G*s and *O*s in Village *i* are given by $Q_i^G = q_i^G\left(X_i\right)N_i$ and $Q_i^O = q_i^O\left(1 - X_i\right)N_i$, respectively. Because of their privileged access, *O*s in Village 1 are less constrained by the higher upper bound on the amount of water they can steal ($q_1^O \le \mathrm{Q/N_1}$). At the same time, *G*s in Village 1 rely on their upstream position to extract water to bring their actual amount as close as possible to allocated amount, i.e., $q_1^G = \min\left[Q/N^G, (Q - Q_1^O)/N_1^G)\right]$. It follows, then, that $q_2^O \le \left[\mathrm{Q\text{-}Q_1^G\text{-}Q_1^O}\right]/\mathrm{N_2}$ is the upper bound on the amount of water that *O*s in Village 2 can steal. Finally, *G*s in Village 2 obtain the amount $q_2^G = \left[Q - Q_1^O - Q_1^G - Q_2^O\right]/N_2^G$. Note that *O*s in Village 1 face an upper-bound on the amount of they obtain, i.e., $\le Q/N_1$. This constraint derives from our assumption that both *G*s and *O*s in Village 1 compete for water at the same time and they are symmetric in their capacity for competing for water (i.e., equal access to water and symmetry in available labor, technology, and skills). For the same reason, *O*s in Village 2 face an upper-bound on the amount of they obtain, i.e., $\leq (Q - Q_1^O - Q_1^G)/N_1$.

The actions stipulated by the rules and the actual actions of *G*s and *O*s in Villages 1 and 2 under the asymmetric setting are given in the following tables (when $L_m \geq \psi - \epsilon$). Note that $\Omega = \delta\left(\frac{X_1 + X_2}{2}\right)\left(1 - \sigma\frac{Q(L_m)}{Q(L_m^*)}\right)$ and the actual values of q_1^O and q_2^O should be below the specified limit, i.e., $q_1^O \leq Q/N_1$ and $q_2^O \leq (Q - Q_1^G - Q_2^G)/N_2$.

The values of $l_{i,f}^G$ (where $i = 1,2$, that refers to the village *i* are obtained by the following optimization problem:

$$\max_{l_{i,f}^G} : \left[c_i\left(l_{i,f}^G\right)^j\left(q_i^G + r_i\right)^k + w\left(l_{i,e}^G\right)\right]$$

$$\text{subject to} \quad l_{i,f}^G + l_{i,e}^G = l - l_{i,m}^G$$

Table A.1. The decisions of Gs and Os in Village 1 for Case 1.

Var.	Rule	Actual
l_m^G	$L_m^*\left(\frac{1}{N}\right)$	$L_m^*\left(\frac{1}{N}\right)$
q_1^G	$\frac{Q}{N^G}$	$\min\left[\frac{Q}{N^G}, \frac{Q - Q_1^O}{N_1^G}\right]$
l_f^G	N/A	$\left[\frac{j\, c_1(q_1^G + r_1)^k}{w^G}\right]^{\frac{1}{1-j}}$
l_e^G	N/A	$l - l_f^G$
l_m^O	$L_m^*\left(\frac{1}{N}\right)$	0
q_1^O	$\frac{Q}{N^G}$	$\left[c_1\left(\frac{k}{\Omega}\right)^{1-j}\left(\frac{j}{w^O}\right)^j\right]^{\frac{1}{1-j-k}} - r_1$

l_f^O	N/A	$\left[c_1 (j/w^O)^{1-k} (k/\Omega)^k\right]^{\frac{1}{1-j-k}}$
l_e^O	N/A	$l_e^O = l - l_f^O$

Table A.2. The decisions of Gs and Os in Village 2 for Case 1.

Var.	Rule	Actual
l_m^G	$L_m^* \left(\frac{1}{N}\right)$	$L_m^* \left(\frac{1}{N}\right)$
q_2^G	$\frac{Q}{N^G}$	$\frac{Q - Q_1^O - Q_1^G - Q_2^O}{N_2^G}$
l_f^G	N/A	$\left[\frac{j\, c_2 (q_2^G + r_2)^k}{w^G}\right]^{\frac{1}{1-j}}$
l_e^G	N/A	$l - l_f^G$
l_m^O	$L_m^* \left(\frac{1}{N}\right)$	0
q_2^O	$\frac{Q}{N^G}$	$\left[c_2 \left(\frac{k}{\Omega}\right)^{1-j} \left(\frac{j}{w^O}\right)^j\right]^{\frac{1}{1-j-k}} - r_2$
l_f^O	N/A	$\left[c_2 (j/w^O)^{1-k} (k/\Omega)^k\right]^{\frac{1}{1-j-k}}$
l_e^O	N/A	$l_e^O = l - l_f^O$

The values of $l_{1,f}^O, q_1^O$ can also be obtained by the following optimization problem:

$$\max_{l_f^O, q_1^O} : \left[c_1 \left(l_f^O \right)^j \left(q_1^O + r_1 \right)^k + w l_e^O - \delta \left(1 - \sigma \frac{Q(L_m)}{Q(L_m^*)} \right) q_1^O \left(\frac{X_1 + X_2}{2} \right) \right]$$

$$\text{subject to } \; l_f^O + l_e^O = l; \;\; q_1^O \le \frac{\mathrm{Q}}{\mathrm{N}_1}$$

and that for $l_{2,f}^O, q_2^O$ from:

$$\max_{l_f^O, q_2^O} : \left[c_2 \left(l_f^O \right)^j \left(q_2^O + r_2 \right)^k + w l_e^O - \delta \left(1 - \sigma \frac{Q(L_m)}{Q(L_m^*)} \right) q_2^O \left(\frac{X_1 + X_2}{2} \right) \right]$$

$$\text{subject to } \; l_f^O + l_e^O = l; q_2^O \le \frac{\mathrm{Q}\text{-}\mathrm{Q}_1^{\mathrm{O}}\text{-}\mathrm{Q}_1^{\mathrm{G}}}{\mathrm{N}_2}$$

- Case 2 ($0 \le L_m \le \psi - \epsilon$)

In this region, the maintenance labor is $L_m^* = 0$; hence, $Q = I(L_m^*)S = 0$. This means that no irrigated water is produced in the system. As a result, water theft and rule enforcement do not exist. In this case, the payoffs of *G*s and *O*s in Village *i* are modified to: $\pi_i^G = f(l_f^G, q_i^G, a) + w l_e^G$ and $\pi_i^O = f(l_f^O, q_i^O, a) + w l_e^O$, respectively. The values of $l_{1,f}^G$, $l_{1,f}^O$, $l_{2,f}^G$, and $l_{2,f}^O$ can be derived by the following optimization (note that $q_i^G = q_i^O = 0$ because there is no irrigated water):

$$\max_{l_{i,f}^I} : \left[c_i \left(l_{i,f}^I \right)^j \left(r_i \right)^k + w^I \left(l_e^I \right) \right]$$

$$\text{subjectto} : l_{i,f}^I + l_{i,e}^I = l$$

where $i = 1, 2$ and $I = G, O$. The actions stipulated by the rules and the actual actions of *G*s and *O*s in Villages 1 and 2 under the asymmetric setting are given in the following Tables (when $0 \le L_m \le \psi - \epsilon$)..

Table A.3. The decisions of Gs and Os in Village 1 for Case 2.

Var.	Rule	Actual
l_m^G	N/A	0
q_1^G	N/A	0
l_f^G	N/A	$(j c_1 r_1^k / w^G)^{\frac{1}{1-j}}$

l_e^G	N/A	$l - l_{1,f}^G$
l_m^O	N/A	0
q_1^O	N/A	0
l_f^O	N/A	$(jc_1 r_1^k / w^O)^{\frac{1}{1-j}}$
l_e^O	N/A	$l - l_{1,f}^O$

Table A.4. The decisions of Gs and Os in Village 2 for Case 2.

Var.	Rule	Actual
l_m^G	N/A	0
q_2^G	N/A	0
l_f^G	N/A	$\left(jc_2 r_2^k / w^G\right)^{\frac{1}{1-j}}$
l_e^G	N/A	$l - l_{2,f}^G$
l_m^O	N/A	0
q_2^O	N/A	0

l_f^O	N/A	$\left(jc_2r_2^k / w^O\right)^{\frac{1}{1-j}}$
l_e^O	N/A	$l-l_{2,f}^O$

A.6. Effect of maintenance threshold

Figure A.3 shows that the maintenance threshold determines the dominance of the three regimes. As the threshold gets lower and gentler in slope (ϵ approaches ψ), *ALL-O*s loses resilience, i.e., its basin of attraction shrinks. At the same time, *MOSTLY-G*s emerges and expands. But this regime shift occurs at the cost of emergence of the *DECOUPLED* regime and more free riders in Village 1 of the *MOSTLY-G*s regime (the red dot for *MOSTLY-G* moving to left as ϵ approaches ψ in Figure A.3). The opposite is true when the threshold gets higher and sharper in slope (ϵ approaches zero). These results suggest that low-threshold scalable systems (i.e., $\epsilon \approx \psi$) are less likely to collapse, but are more prone to economic inequality. Conversely, centralized capital-intensive systems (i.e., $\epsilon \approx 0$) are less likely to have inequality issues, but are much more likely to collapse.

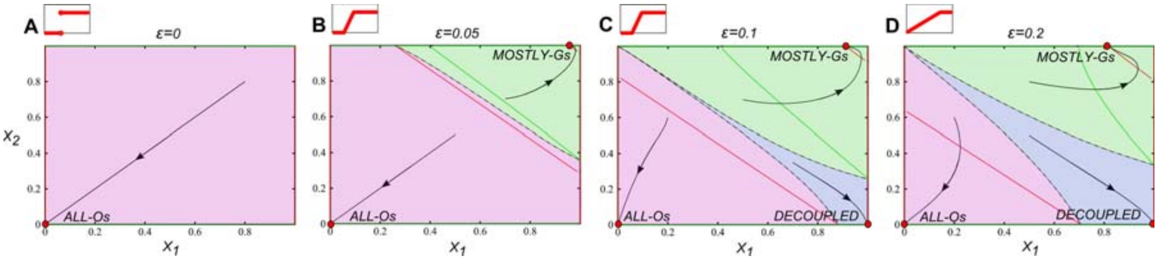

Figure A.3. Effect of maintenance threshold on system behavior. Note that half-saturation point of labor is 0.2, i.e., $\psi = 0.2$. The three regimes shrink and expand as ϵ is varied (Panels A to D). The small inset graphs next to the panel labels show the shape of the infrastructure-labor relation for each value of ϵ. Except for the focal parameter, the same default parameter values were used as in Figure A.2.

A.7. Parameters

The parameters of output elasticities for labor, water, and acreage are set to $j = 0.3$, $k = 0.4$, and $1-j-k = 0.3$, respectively. These values reflect that the three inputs of production have more or less similar effects on agricultural yield. Agricultural yield is chosen as a numeraire good ($p = 1$). Wage is set low ($w = 0.2$) to represent that farmers have little opportunity cost for living as farmers, i.e., they live in isolated rural areas with little or no alternative options for livelihood other than farming. Number of farmers or households in each village is set to a modest value ($N_1 = N_2 = 50$). Half-saturation point of L_m is set to 0.2 (20% of total labor) to represent that the irrigation infrastructure consumes a considerable amount of repair labor every year. Productivity coefficient for the inputs of production (*b*), acreage of farmer (*a*), and available labor per farmer (*l*) are all set to 1 to ease calculations.

Table A.5. Default parameter values for the irrigation model.

Symbol	Definition	Value(s)
w	Wage for outside employment.	0.2
ψ	Half-saturation point of L_m yielding $I_{max}/2$ infrastructure efficiency.	0.2
ϵ	Half-width of the threshold slope for infrastructure maintenance.	0.125
I_{max}	Maximum infrastructure efficiency.	1.0
j,k	Output elasticities of farming labor and irrigated water for agricultural yield, respectively.	$j = 0.3, k = 0.4$
p	Price per unit of agricultural yield.	1.0
b	Productivity coefficient for the inputs of production.	1.0
a_i	of farmer in Village *i*	$a_1 = a_2 = 1$
l	Available labor per farmer.	1.0
N_i	Number of farmers in Village *i*.	$N_1 = N_2 = 50$
R	Total amount of freely-available alternative water.	0
r_i	Amount of alternative water available to a farmer in Village *i*.	0
γ_s, γ_o	Maximum enforcement costs for monitoring opportunists in the same village and the other village, respectively.	0.05, 0.1
δ	Maximum penalty cost imposed on opportunists.	1.4
σ	Tolerance for water theft shown by group-conformists when water is abundant in the system (≤ 1.0).	0.9

APPENDIX B

SUPPORTING INFORMATION FOR CHAPTER 3

B.1. Forest growth in Geumsan from 1976 to 2010

The overall forest cover of Geumsan, South Korea increased by a factor of 13.4 between 1976 and 2010.

Table B.1. Trends in forest cover in Geumsan from 1976 to 2010.

Year	Growing stock (m^3)
1976	327,468
1995	1,116,566
2000	1,445,177
2005	2,559,201
2010	4,410,952

Source: KFS 2013, KNSO 2013

B.2. Model selection

We studied the factors determining cooperative transformation by means of multivariate logistic-regression models. Contextual factors included two factors (spatial extent of villages and size of the resource system), four continuous variables (number of villages, existence of tenant fees, ratio of cross-institutional links, andtopographic location of villages), and one dichotomous variable (terrain of resource system). Our dependent variables (type of transformation) is dichotomous (1 if cooperative transformation and 0 if non-cooperative transformation). See Table Table B.2 for the values given to each variable.

Table B.2. Values of the contextual variables in *songgye*.

Variables	Values
Existence of tenant fees	1: annual tenant fees were collected 0: otherwise
Number of villages	Continuous. Range: 1-39
Ratio of cross-institutional links	Continuous. Range: 0-1
Spatial extent of villages	0: one village is involved; 1: multiple villages are involved but all are situated within one sub-district 2: multiple villages are involved and are situated over multiple sub-districts
Size of resource system	0: 1-10 hectares 1: 11-100 hectares

Terrain of resource system	2: greater than 100 hectares 1: considerable dry-field farming exists 0: otherwise
Topographic location of villages	Continuous. Range: 0.05-0.61

We used a model selection approach (Johnson and Omland 2004)to determine which sets of combinations of factors better explain cooperative transformation. We applied the Akaike Information Criterion (AIC) method to compare the fits of all possible combinations of explanatory variables (Burnham and Anderson 2002).AIC is calculated for a suite of models and the best-fitting model has the smallest AIC. The absolute size of the AIC is unimportant; instead the difference in AIC values between the best fitting model and the others models (Δ_i) indicates the relative support for the models. In order to compare models, we calculate Akaike weights (w) as the probability that a model would be selected as the best fitting model if the data were collected again under identical circumstances (Burnham and Anderson 2002):

$$w_i = \frac{\exp\left(-0.5 * \Delta_i\right)}{\sum_{r=1}^{R} \exp\left(-0.5 * \Delta_r\right)}$$

Where w_i is the Akaike weights for model i; $\Delta_i$is the different between the AIC of the best fitting model and that of model i. The numerator is the relative likelihood of the the model i. The denominator calculates the sum of the relative likelihoods for all candidate models.

For the set of models, Akaike weights sum to 1. A model whose Akaike weight is close to 1 is unambiguously supported by the data (Burnham and Anderson 2002). We consider as plausible models those with Akaike weights that are within 10% of the highest weight. We also calculated the relative variable importance as the sum of Akaike weights over all models including the explanatory variable. The relative variable importance is the probability that, of the variables considered, a certain variable is in the best approximating model. We calculated the model averaged estimates weighted by its Akaike weight (Burnham and Anderson 2002). Model-averaged parameter estimates are only calculated for those independent variables that are included in the confidence set of models.

All analyses were conducted using the R Project for Statistical Computing package, particularly applying the package MuMln.

APPENDIX C

THE FUZZY-SET QCA RESULTS FOR CHAPTER 4

Table C.1. Fuzzy-set values of all conditions and the outcome for the group performance under environmental stability. See Appendix B for the definitions of the variables.

Group #	Treatment	Outcome	Conditions					
		PERFORM	COORD	INNER	OUTER	UPART	KNOW	MOREF
1	I-LV	0.99	0.67	1	1	1	0.33	0.67
2	I-LV	0.98	0.33	0.67	0.67	0.67	0.67	0.33
3	I-LV	0.92	0.67	0.67	1	1	0.67	0.67
4	I-LV	0.98	0.67	0.67	1	1	0.67	0.67
5	I-LV	0.01	0	0	0	0.33	0.33	0
6	I-HV	0.97	0.33	0.33	0.33	0.33	0.67	0.33
7	I-HV	0.98	0.67	0.67	1	1	1	0.67
8	I-HV	0.85	0.67	0.33	0.67	0.67	0.33	0.67
9	I-HV	0.99	0.67	1	1	1	0.33	0.67
10	I-HV	0.95	0.67	0.67	0.67	0.33	0.67	0.67
11	I-HV	0.98	0.67	0.33	0	0.67	0.33	0.67
12	W-LV	0.03	0	0	0.33	0.33	0.67	0
13	W-LV	0.96	0	0	0	0.67	0.33	0
14	W-LV	0.98	0.67	1	0.67	0.67	0.33	0.67
15	W-LV	0.99	0.67	0.67	0.67	0.33	0.67	0.67
16	W-LV	0.98	0.33	0.67	0.67	0.33	0.33	0.33
17	W-HV	0.94	0.33	0.67	0.67	0.67	0.67	0.33
18	W-HV	0.98	0.33	0.67	0.67	0.67	0.67	0.33
19	W-HV	0.98	0.33	0.33	0.67	0.33	0.33	0.33
20	W-HV	0.97	0.67	0.33	0.67	0.67	0.33	0.67
21	W-HV	0.99	1	0.67	1	0.67	0.67	1

Table C.2. Fuzzy-set values of all conditions and the outcome for the robustness of group performance under environmental uncertainty. See Appendix B for the definitions of the variables.

Group #	Treatment	Outcome	Conditions					
		ROBUST	COORD	INNER	OUTER	UPART	KNOW	MOREF
1	I-LV	0.99	0.67	1	1	1	0.33	0.67
2	I-LV	1	0.33	0.67	0.67	0.67	0.67	0.33
3	I-LV	0.96	0.67	0.67	1	1	0.67	0.67
4	I-LV	0.99	0.67	0.67	1	1	0.67	0.67
6	I-HV	0.32	0.33	0.33	0.33	0.33	0.67	0.33
7	I-HV	0.99	0.67	0.67	1	1	1	0.67
8	I-HV	0.51	0.67	0.33	0.67	0.67	0.33	0.67
9	I-HV	0.92	0.67	1	1	1	0.33	0.67
10	I-HV	0.89	0.67	0.67	0.67	0.33	0.67	0.67
11	I-HV	0.03	0.67	0.33	0	0.67	0.33	0.67
13	W-LV	0.01	0	0	0	0.67	0.33	0
14	W-LV	0.99	0.67	1	0.67	0.67	0.33	0.67
15	W-LV	0.99	0.67	0.67	0.67	0.33	0.67	0.67
16	W-LV	0.97	0.33	0.67	0.67	0.33	0.33	0.33
17	W-HV	0.77	0.33	0.67	0.67	0.67	0.67	0.33
18	W-HV	0.04	0.33	0.67	0.67	0.67	0.67	0.33
19	W-HV	0.22	0.33	0.33	0.67	0.33	0.33	0.33
20	W-HV	0.96	0.67	0.33	0.67	0.67	0.33	0.67
21	W-HV	0.84	1	0.67	1	0.67	0.67	1

Table C.3. Truth table for the analysis of sufficiency for the group performance under environmental stability.

COORD	INNER	OUTER	UPART	KNOW	MOREF	PERFORM	N	Consist.	Group #
1	1	1	1	1	1	1	4	1	3,4,7,21
0	1	1	1	1	1	1	3	1	2,17,18
1	1	1	1	0	1	1	3	1	1,9,14
1	0	1	1	0	1	1	2	1	8,20
1	1	1	0	1	1	1	2	1	10,15
0	1	1	0	0	1	1	1	1	16
1	0	0	1	0	1	1	1	1	11
0	0	1	0	0	1	0	1	0.924433	19
0	0	0	1	0	1	0	1	0.875	13
0	0	0	0	1	1	0	2	0.818868	6,12
0	0	0	0	0	1	0	1	0.806452	5

Cutoff consistency: 0.95

Table C.4. Truth table for the analysis of sufficiency for the robustness of group performance under environmental uncertainty. Both the high- and low-variability treatments (N=19) are considered.

COORD	INNER	OUTER	UPART	KNOW	MOREF	ROBUST	N	Consist.	Group #
1	1	1	1	1	1	1	4	0.941176	3,4,6,19
1	1	1	1	0	1	1	3	0.934921	1,8,12
1	1	1	0	1	1	1	2	0.911638	9,13
0	1	1	0	0	1	1	1	0.896726	14
1	0	1	1	0	1	1	2	0.885312	7,18
0	1	1	1	1	1	1	3	0.880952	2,15,16
0	0	1	0	0	1	0	1	0.793956	17
1	0	0	1	0	1	0	1	0.735516	10
0	0	0	0	1	1	0	1	0.681395	5
0	0	0	1	0	1	0	1	0.681395	11

Cutoff consistency: 0.85

Table C.5. Truth table for the analysis of sufficiency for the robustness of group performance under environmental uncertainty. Only the high-variability treatments (N=11) are considered.

COORD	INNER	OUTER	UPART	KNOW	MOREF	ROBUST	N	Consist.	Group #
1	1	1	1	1	1	1	2	0.896985	2,11
1	1	1	1	0	1	1	1	0.876133	4
1	1	1	0	1	1	1	1	0.862416	5
1	0	1	1	0	1	1	2	0.828313	3,10
0	1	1	1	1	1	1	2	0.794521	7.8
0	0	1	0	0	1	0	1	0.716981	9
1	0	0	1	0	1	0	1	0.647651	6
0	0	0	0	1	1	0	1	0.647651	1

Cutoff consistency: 0.75

Table C.6. Tests for the analysis of sufficiency for the two outcome variables. Tests for the analysis of sufficiency cover group performance, the robustness of group performance based on high- and low-variability treatments, and the robustness of group performance based on high-variability treatment only.

Presence of outcome	fsQCA results
Performance (N=21)	Intermediate solution: INNER*OUTER*MOREF COORD*UPART*MOREF Solution Coverage: 0.635870 Solution Consistency: 0.999146
Robustness: High- and low-variability (N=19)	Intermediate solution: INNER*OUTER*MOREF COORD*OUTER*UPART*MOREF Solution Coverage: 0.750560 Solution Consistency: 0.910326
Robustness: High-variability (N=11)	Intermediate solution: COORD*OUTER*UPART*MOREF INNER*OUTER*UPART*KNOW*MOREF INNER*OUTER*COORD*KNOW*MOREF Solution Coverage: 0.787365 Solution Consistency: 0.848837

APPENDIX D

CODING PROTOCOL FOR CHAPTER 4

I. Outcome variables

1. Group performance under environmental stability (PERFORM)

The number of tokens earned by groups in rounds 6 to 10 is our base measure for group performance under environmental stability. The mean and the median values of this measure are 249 and 268 tokens, respectively, with the minimum of 58 and the maximum of 301, i.e., a left-skewed distribution. Among 21 groups, 16 earned at least 250 tokens or more during that round interval. Hence, we decided that the total earnings of 250 tokens is the threshold for high group performance. For the threshold of poor group performance, we used our subjective judgment to set that total earnings below 100 tokens clearly indicate poor performance. This threshold is consistent with the two groups that plainly failed in maintaining the irrigation system (groups 5 and 12). These two groups earned less than 100 tokens. We used these two thresholds to calibrate the measure to a continuous scale of 0–1.0 (0 being 'clearly low performance'; 1.0 being 'clearly high performance'). We used the calibration function of fs/QCA (a software tool for QCA analysis developed by Charles Ragin) to calibrate the measure into that continuous scale.

2. Robustness of group performance under environmental uncertainty (ROBUST)

The ratio of group earning from water harvest in rounds 11 to 15 (rounds with uncertainty) to that in rounds 6 to 10 (rounds with stability) is our base measure for robustness of group performance under environmental uncertainty. The ratio values around 1.0 indicate little or no change in group performance under uncertainty. If the ratio is considerably below 1.0, it means a large drop in group performance under uncertainty. Barring the two groups that performed poorly in rounds 6 to 10 (groups 5 and 12), the mean and the median values of the ratio are 0.82 and 0.86, respectively, with the maximum of 1.06 and the minimum of 0.36. Here, we used our educated judgment to define the thresholds for 'clearly robust' and 'clearly fragile' outcomes. We decided that a ratio value above 0.9 indicates a 'clearly robust' outcome, i.e., 10% or less drop in performance under uncertainty. It was also decided that a ratio value below 0.5 indicates a 'clearly fragile' outcome, i.e., 50% or more drop in performance under uncertainty. We used these two thresholds to calibrate the measure to a continuous scale of 0–1.0 (0 being 'clearly fragile'; 1.0 being 'clearly robust'). We used fs/QCA to do the calibration.

II. Coding of the causal conditions at the round-level

1. Group coordination

Analyze both actual actions (how much tokens are invested and how much tokens are earned from water harvest) of group participants and group communication content in a given round. If the data suggest that three or more participants followed shared strategies for both investment and harvest decisions, we assume that group coordination exists in that round.

Consider the following example. If group participants proposed for investment of 5 tokens and 10-tokens-worth of harvest during group chat session of previous round(s) and their actual actions show that three or more of them followed BOTH proposals (see the table below), we assume that group coordination exists in that round.

	Tokens for investment					Tokens earned from harvest				
Participant	A	B	C	D	E	A	B	C	D	E
Decisions	5	5	4	5	5	15	10	10	10	4

Consider another example. If group participants proposed for investment of 5 tokens and 10-tokens-worth of harvest during group chat session of previous round(s) and their actual actions show that three or more of them followed ONLY one of the proposals (see the table below), we assume that group coordination does not exist in that round.

	Tokens for investment					Tokens earned from harvest				
Participant	A	B	C	D	E	A	B	C	D	E
Decisions	5	5	4	5	5	15	15	10	4	4

Consider the same example. If actual actions of group participants show that three or more of them followed NEITHER of the proposals (see the table below), we assume that group coordination does not exist in that round.

	Tokens for investment					Tokens earned from harvest				
Participant	A	B	C	D	E	A	B	C	D	E
Decisions	1	3	4	5	5	15	15	10	4	4

Some caveats or exceptions apply:

a) If some participants invest slightly more or slight less tokens than others based on voluntary decision or approval from others (if plans for such deviations are stated during group discussion and done to complement shared strategies), their decisions are still counted toward group coordination.

b) Exclude cases where upstream participants (A, B, and C) and downstream participants (D and E) are in conflict (participants A, B, and C invest a same amount of tokens but downstream participants invest little or none in retaliation).

c) Exclude cases in which three or more participants harvested for 4 tokens (unless there is clear sign of reduced water delivery capacity).

d) Consider for rotating investments, e.g., participants agree to alternate who invest more in a round (investment amounts don't have to be exact as long as alternating pattern is observed).

2. Inner-loop management trial and learning

Presence of a group strategy adhered by participants and whether there is a change in such a shared strategy are a sign of inner-loop management trial and learning. If the experimental data show that the majority of participants in a group (three or more participants) follow a same rule for either investment or harvest decision in a given round, we assumed that a group strategy is present in that round. If there is a change in such a group strategy to better meet an existing goal, an inner-loop trial may be in play.

Group action	Cues for inner-loop management trial and learning
Investment	Any change in the number of tokens invested for infrastructure in group strategy to better meet an existing goal (e.g., group strategy switches to 'each must invest 5 tokens' from 'each must invest 8 tokens' in the previous round to achieve 66% infrastructure efficiency).
Harvest	Any change in the following aspects of group strategy for water harvest to better meet an existing goal. *1) How much to harvest.* ▪ Time-based (e.g., harvest for 10 seconds). ▪ Quantity-based (e.g., stop at 250 units of water, stop at earning 10 tokens). *2) Method of harvest.* ▪ Sequential: Players take sequential turns in opening gates to harvest water ▪ Rotation: Players rotate which player(s) get most of the water in a given round *3) Order of harvest.* ▪ Forward: Harvest from participant A to participant E. ▪ Reverse: Harvest from participant E to participant A. *4) Special rules.* ▪ Water wastage prevention: Participant E always leaves gate open . ▪ Rotate extra water: Rotate which player(s) get little more water in a given round.

Some caveats or exceptions apply:

a) A coordinated group action may exist and change without a clear reference to underlying assumption or social goals. We do not count that situation as an inner-loop trial.
b) If group participants adopt a strategy for rotation in investment or harvest levels, we do not count it as an inner-loop trial even if amount of investment or harvest constantly changes every round.

3. Outer-loop management trial and learning

Outer-loop management trial and learning can be detected when the experimental data show that group strategies for either the investment or water harvest decision is revised or updated to meet a new social goal.

Group action	Types of underlying assumption or social goal

Investment	The following types of assumption or goals are generally observed as group participants deliberate for investment decision. 1) *Invest for high infrastructure efficiency*: Participants aim to reach and stay around 100% infrastructure efficiency. 2) *Invest for optimal infrastructure efficiency*: Participants aim to reach and stay around 66~70% infrastructure efficiency. 3) *Invest for moderate infrastructure efficiency*: Participants aim to reach and stay somewhere between 66~70% and 100% efficiencies. 4) *One of above three & proportional investment*: Participants expect those with slightly more or less water harvest should be compensated by investing slight more or less. 5) *Invest for robustness*: Participants aim to invest more tokens than usual to prepare for a catastrophic damage to the infrastructure. 6) None
Water harvest	The following types of assumption or goals are generally observed as group participants deliberate for water harvest decision. 1) *Equal harvest*: Participants aim to harvest an equal amount of water. 2) *Equal harvest & Efficiency*: In addition to harvesting water equally, participants want to reduce or prevent water wastage (i.e., unused water that exit the system). 3) *Proportionality*: Participants generally agree those who do not invest should get zero water or vice versa (e.g., I am not investing, so I am OK with getting little or no water).

Some caveats or exceptions apply:

a) Repeatedly going over 100% for the infrastructure efficiency likely means that there is no underlying assumption or social goal for investment.
b) We assume that underlying assumption or social goals tend to have continuing presence once established. Hence once we detect a clear sign of assumption or goal in a round, we assume that it is present in the subsequent rounds unless we clearly see that there is a change.

4. User participation

Analyze the content of group communication to assess user participation in decision-making process in a given round. If two or more participants propose an unique group strategy for either investment or harvest decision (irrespective of whether or not such a proposal is followed by others), we assume that multiple users are participating in the decision-making process in that round. For example, statements like "we should invest 5 tokens each" may count as a proposal. Repeating the proposals mentioned by others do not count as an unique proposal. Note that we only consider proposals for shared group strategy, not plans for individual actions. For example, statements like "I will invest 5 tokens" don't count as a proposal for group strategy, unless the context of the group discussion shows that such a statement is really intended for group strategy.

5. Knowledge-sharing

Analyze the content of group communication to assess the presence of knowledge-sharing in a given round. Shared knowledge can be about rules about the experiment, insight about how the experiment should be played, and any answer given to a question (investment or harvest-related) raised by participants during group discussion. For example, statements like "it could be at 80% or 90% efficiency and still be ok" count as a knowledge-sharing for investment decisions.

6. Monitoring and reflection

Analyze the content of group communication to assess the presence of monitoring and reflection. If a participant makes comments related to the following items, we count it as a sign of monitoring and reflection in that round:

a) Outcomes or behaviors of individuals or the whole group (e.g., "A is hogging water", "that was a bad round", "it didn't work")
b) Current biophysical conditions (e.g., "current infrastructure efficiency is 55%")
c) Raising issues or trying to correct mistakes or opportunistic behaviors of specific individuals (e.g., " hey A, close your gate ", " I'm not investing because upstream guys are not giving us water").

III. Aggregating the round-level coding results

1. Does this group have tight group coordination (COORD)?
(0=No, 0.33=More no than yes, 0.67=More yes than no, 1.0=Yes)

Count the number of rounds with group coordination (among rounds 1 to 10 and the last practice round). Divide this count by 11 to derive average group coordination per round.

If this average is in the interval [0, 0.165), result is 0.
If this average is in the interval [0.165, 0.495), result is 0.33.
If this average is in the interval [0.495, 0.835), result is 0.67.
If this average is in the interval [0.835, 1], result is 1.0.

2. Does this group actively engage in inner-loop management trial and learning (INNER)?
(0=No, 0.33=More no than yes, 0.67=More yes than no, 1=Yes)

Count the number of rounds with inner-loop management trial and learning (among rounds 1 to 10 and the last practice round). Divide this count by 11 to derive average inner-loop trial per round.

If this average is in the interval [0, 0.165), result is 0.
If this average is in the interval [0.165, 0.495), result is 0.33.
If this average is in the interval [0.495, 0.835), result is 0.67.
If this average is in the interval [0.835, 1], result is 1.

3. Does this group actively engage in outer-loop management trial and learning (OUTER)? (0=No, 0.33=More no than yes, 0.67=More yes than no, 1=Yes)

0 if one of the following conditions are met:

- There was no change in general strategy in the rounds.
- There was only one change in appropriation general strategy (only "Equal" appears) in entire rounds (P2-R10).

0.33 if the following condition is met:

- There was little or no change in general strategy in early rounds (P2-R5) . However, in later rounds (R6-R10), there was one or two changes in general strategy.

0.67 if the following condition is met:

- There were changes in BOTH appropriation and provision general strategies in early rounds (P2-R5). However, in later rounds (R6-R10), there was no change in general strategy.

1 if the following condition is met:

- There were changes in BOTH appropriation and provision general strategies in early rounds (P2-R5). In later rounds (R6-R10), there were one or two changes in general strategy.

4. Does this group have active user participation (UPART)?

Count the number of rounds with user participation (among rounds 1 to 10 and the last practice round). Divide this count by 11 to derive average user participation per round.

If this average is in the interval [0, 0.165), result is 0.
If this average is in the interval [0.165, 0.495), result is 0.33.
If this average is in the interval [0.495, 0.835), result is 0.67.
If this average is in the interval [0.835, 1], result is 1.

5. Does this group actively share knowledge (KNOW)?

Count the number of rounds with knowledge-sharing (among rounds 1 to 10 and the last practice round). Divide this count by 11 to derive average knowledge-sharing per round.

If this average is in the interval [0, 0.165), result is 0.

If this average is in the interval [0.165, 0.495), result is 0.33.
If this average is in the interval [0.495, 0.835), result is 0.67.
If this average is in the interval [0.835, 1], result is 1.

6. Does this group monitor and reflect on outcomes (MOREF)?

Count the number of rounds with monitoring and reflection (among rounds 1 to 10 and the last practice round). Divide this count by 11 to derive average monitoring and reflection per round.

If this average is in the interval [0, 0.165), result is 0.
If this average is in the interval [0.165, 0.495), result is 0.33.
If this average is in the interval [0.495, 0.835), result is 0.67.
If this average is in the interval [0.835, 1], result is 1.