THE EVOLUTION OF COOPERATION IN COMMON-POOL RESOURCES

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THE EVOLUTION OF COOPERATION IN COMMON-POOL RESOURCES

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Abstract

The prevalence of cooperation among appropriators in common-pool resources contradicts the predictions of the theory of collective action. Understanding the factors that affect the propensity for appropriators to cooperate will yield insights into the role of institutions and social norms in managing resources. An evolutionary game theory model is constructed to show the emergence and stability of a cooperative equilibrium subject to initial conditions. A logit regression model is used to determine the effect social, institutional, and physical variables have on the probability of a cooperative equilibrium emerging in irrigation systems in Nepal. The system location and type of management structure are found to affect the likelihood of cooperation and efficient use of the resource.

KEYWORDS: (common-pool resource, irrigation, Nepal)

ON MY HONOR, I HAVE NEITHER GIVEN NOR RECEIVED UNAUTHORIZED AID ON THIS THESIS

Signature

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CHAPTER 1

INTRODUCTION

The study of common-pool resources has provided a unique framework through which to analyze human behavior within the context of collective action, institutional economics, and resource management. The small-scale nature of many common-pool resources, in contrast to larger collective action problems like roads and public defense that manifest themselves on the state or national levels, makes the methodology of fieldwork much more feasible. As such, common-pool resource can be analyzed to inform how people behave in a collective setting. The analysis or cases, coupled with experimental results from public goods and common-pool resource games, has vastly expanded the study of collective action beyond the theoretical models that have permeated economic and policy thought since the second half of the 20th century. This study seeks to add to the growing body of literature by the analyzing social, physical, and institutional variables that affect cooperation and efficient allocation in a specific common-pool resource, irrigation systems in Nepal.

Beyond providing additional data through which to analyze collective action problems, an empirical study of the determinants of cooperation in irrigation systems in Nepal has major policy ramification. The study of common-pool resources provides not only a lens through which to understand collective action, but also a means of analyzing effective natural resource management strategies and economic development policies. For instance, the standard policy prescription to deal with collective action and commons problems has been either privatization or state management. By contrast, the analysis of irrigation systems highlights the effectiveness of self-governance to efficiently allocate resources in a manner that addresses the problem of overexploitation that stems from concentrated benefits and diffused costs of extracting from a common resource. In the realm of resource management policy, this represents a transformative shift away from the pessimistic predicted outcome of overexploitation arising from rational actors maximizing short-term profit. Within the context of the Nepalese irrigation systems, this realization has helped to alter irrigation policy in a country characterized by underperforming economic development despite abundant resources, particularly water.[1]

The context afforded by the combination of case studies and experiments on common-pool resources has another, more significant advantage. The prevalence of empirical data from fieldwork broadens the analysis of collective action to include institutional, physical, and social factors that often cannot be observed in a laboratory setting. The result is that to keep pace with the observation of cooperative behavior, the theory of common-pool resources has moved beyond the strict rational actor models that have dominated economic thought and policy for the last 50 years. While this is not to say that such models are necessarily antiquated or that the emerging theory of cooperation in common-pool resources through evolutionary game theory models applies beyond the specific context of common-pool resources, it does indicate that common-

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[1] The case of Nepalese irrigation will be discussed in detail in Chapter 4.

pool resource literature is beginning to encompass factors outside of the rational actor model in order to explain the prevalence of cooperation in the empirical data.

Overview of Present Study

Chapter 2 provides a literature review of the history of collective action and common-pool resource theory. The traditional models of collective action are presented, followed by theoretical critiques specific to the unique nature of common-pool resources. Empirical evidence of cooperation is then reviewed before turning to the theories that seek to explain the emergence of cooperation in terms of evolutionary game theory.

Chapter 3 discusses the theory of common-pool resources both qualitatively and quantitatively. The design principles of successful common-pool resources are outlined before turning to a game theoretic model of a common-pool resource game. After the formulation of the initial model and a discussion of the Nash equilibrium, evolutionary game theory dynamics are introduced to explain how cooperation can arise in a population starting from the assumption of player type variation in the initial population. The conditions for stability of a "cooperative equilibrium" and "defector equilibrium" are then presented.

Chapter 4 discusses the history of Nepalese irrigation, primarily since the middle of the 20th century, before the data on irrigation systems is analyzed. This context provides additional explanation for the inclusion of certain physical variables in the empirical model. Chapter 5 discusses the data used in the regression analysis and the empirical model. A logit regression model is used to analyze the data. Chapter 5 summarizes the results of the regression and concludes.

CHAPTER 2

LITERATURE REVIEW

The appropriation and provision of common-pool resources (CPR) give rise to a complex set of economic, political, and environmental challenges unlike any encountered by either purely public goods or purely private goods. Natural or man-made CPRs, such as inshore fisheries, irrigation systems, and pastures, are characterized by costly exclusion and exhaustion in consumption. The former quality is a feature of public goods, whereas the latter is associated with private goods.[1] As such, the appropriation and provision of CPRs requires a framework fundamentally different from those used to analyze either purely public or purely private goods. Scholars in fields spanning economics, political science, sociology, and biology have directly and indirectly addressed these appropriation and provision problems through theoretical models, fieldwork, and laboratory experiments.

The field of biology produced much of the early literature on the nature of common-pool resources. As such, much of the analysis neglected the fundamentally economic nature of the problem.[2] A transformative shift in the study of common-pool

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[1] Elinor Ostrom and Roy Gardner, "Coping with Asymmetries in the Commons: Self-Governing Irrigation Systems Can Work," *Journal of Economic Perspectives* 7 (Fall 1993): 93.
[2] H. Scott Gordon, "The Economic Theory of a Common-Property Resource: The Fishery," *Journal of Political Economy* 62 (1954): 124.

resources occurred with H. Scott Gordon's 1954 article, "The Economic Theory of a Common-Property Resource: The Fishery." Within the context of a fishery, Gordon demonstrated that the problem of overfishing "has its roots in the economic organization of the industry."[3] Specifically, Gordon shows that under an imperfect competition model the economic rent yielded will be dissipated because the rent cannot be legally appropriated by anyone.[4] At the heart of this argument is the nature of common property over an exhaustible resource: assuming heterogeneous yields within a CPR[5], an equilibrium based on marginal productivity will not be stable because the appropriators of the common resource will switch to the location with a higher yield. Without property rights, the misallocation of fishing effort will result in overexploitation of the resource.[6] In order to deal with overexploitation and the dissipation of rents, Gordon advocates either privatization or public ownership of the resource.[7]

Traditional Theoretical Models

The notion that privatization or public ownership were the only way of overcoming the overexploitation problems faced by CPRs gained popularity among both scholars and policymakers, largely due to the power of several theoretical models: the tragedy of the commons, the free-rider problem in the provision of public goods, and the n-person Prisoner's Dilemma. The arguments presented in these three theories take

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[3] Ibid., 128.
[4] Ibid. 130-1.
[5] An assumption of a homogeneous distribution across the common-pool resource would simplify the system but ecological studies show that resources like fisheries and pastures are distributed heterogeneously.
[6] Gordon, 131-2.
[7] Ibid., 135.

different forms, but all adopt a pessimistic outlook on the prospect of achieving an efficient outcome based on the disparity between private and collective costs and benefits. The formulations and implications of each of these models will be discussed before turning attention to their critiques in the context of common-pool resources.

Garrett Hardin's seminal essay, "The Tragedy of the Commons," develops a thought experiment in which herdsmen with equal access to a pasture decide how many cattle to graze. Central to the thought experiment are the assumptions that each herdsman will graze as many cattle as possible, each herdsman is rational, and the pasture has a carrying capacity, at which point the commons will deteriorate.[8] Once the commons has reached its carrying capacity, the individual herdsman's decision to add one animal accrues a concentrated benefit and a diffuse, and often time-discounted, cost. As a rational actor, each herdsman will arrive at the same conclusion, locking himself "into a system that compels him to increase his herd without limit—in a world that is limited."[9] This pessimistic conclusion appears unavoidable in the absent some form of coercion or regulation. Although an externally imposed system of rules and sanctions is a perhaps the most common form of coercion, Hardin does leave open the possibility of self-governance through "mutual coercion, mutually agreed upon."[10]

The game theoretic formalization of the tragedy of the commons gave rise to modeling collective action and CPRs as n-player Prisoner's Dilemma games.[11] This

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[8] Garrett Hardin, "The Tragedy of the Commons," *Science* 162 (1968): 1244.
[9] Ibid.
[10] Ibid., 1247.
[11] Elinor Ostrom, *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge: Cambridge University Press, 1990), 3.

model, in fact, became the established representation of collective action problems.[12] The general form of a Prisoner's Dilemma game is one in which, given the strategy space of *Cooperate* and *Defect*, each player has a strictly dominant strategy to defect. The resulting equilibrium of {Defect, Defect} is also Pareto-dominated by {Cooperate, Cooperate}. In the context of common-pool resources, the strategy choices available to each player are to cooperate with a rule of restrained access, or defect and use more than the optimal amount of the resource. Each individual player is assumed to have the following preferences for outcomes: (i) the individual defects while everyone else cooperates; (ii) everyone cooperates; (iii) everyone defects; (iv) the individual cooperates while everyone else defects.[13] The socially optimal outcome is option (ii). However, this equilibrium is unstable in a single-shot Prisoner's Dilemma game because each individual will rationally choose to defect because it will earn a higher payoff. Echoing Hardin's grim forecast in "The Tragedy of the Commons," the paradox of the Prisoner's Dilemma is that individually rational actions lead to collectively irrational outcomes.[14] This non-cooperative equilibrium exists as a strictly dominant strategy under specific assumptions about the nature of play, the level of information, and the time horizon of the game[15]. The conditions under which a cooperative equilibrium can emerge will be discussed below.

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[12] Elinor Ostrom, "Collective Action and the Evolution of Social Norms," *Journal of Economic Perspectives* 14 (2000): 137.
[13] Robert Wade, "The Management of Common Property Resources: Collective Action as an Alternative to Privatization or State Regulation," *Cambridge Journal of Economics* 12 (1987): 97.
[14] Ostrom, *Governing the Commons*, 4.
[15] Wade, 98.

The third model, the free-rider problem, is derived from the theory of public goods. In the seminal paper "The Pure Theory of Public Expenditure," Samuelson lays the foundation for the analysis of the provision of public goods. The central tenet of his theory is the claim that, in the presence of public goods, "it is in the selfish interest of each person to give false signals, to pretend to have less interest…than he really has."[16] The notion that each individual's best strategy is to signal falsely in order to "snatch some selfish benefit"[17] is the cornerstone of the free-rider problem articulated in Olson's *The Logic of Collective Action.*

Olson's path-breaking work on collective action and the free-rider problem challenged the orthodox view that groups tend to act in their collective best interest. Olson argues that

> unless the number of individuals is quite small, or unless there is coercion or some other special device to make individuals act in their common interest, *rational, self-interested individuals will not act to achieve their common or group interest.*[18]

This "zero contribution thesis" formulated by Olson is most compelling in the case of large groups because each individual will receive a smaller portion of the collective benefit, and because organizational costs increase with group size.[19] Small groups are more likely to achieve collective action because an individual can be pivotal in the decision of whether or not to provide a public good. However, in large groups, the

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[16] Paul Samuelson, 'The Pure Theory of Public Expenditure," *The Review of Economics and Statistics* 36 (1954): 388-9.
[17] Ibid.
[18] Mancur Olson, *The Logic of Collective Action* (Cambridge: Harvard University Press, 1965), 2. Emphasis original.
[19] Ibid., 48.

likelihood of being pivotal decreases. This, coupled with the difficulty of monitoring in large groups, increases the incentive to free ride.[20]

The collective action problem can, in fact, be modeled as an n-person Prisoner's Dilemma game. In "Collective Action as an Agreeable n-Prisoner's Dilemma," Russell Hardin constructs a game matrix with players Individual and Collective. He shows that Individual's dominant strategy is to not pay for the collective good. Since each person in the group decides individually, Collective's strategy will be symmetric with Individual's. This modified two-player Prisoner's Dilemma can be generalized to an n-player game in which each player's dominant strategy is not to pay. Thus, the standard Prisoner's Dilemma outcome of a dominant strategy equilibrium that is Pareto dominated will emerge.[21] While the outcome of the n-person game is the same as the Prisoner's Dilemma, Hardin's logic differs slightly from the aforementioned dominant strategy argument. In a collective action problem the dilemma the individual faces does not depend on the other's payoff, but rather on whether anyone else will even play the game. Therefore,

> a rational player in the game of collective action does not refuse to pay merely because his strategy of not paying is dominant and yields a higher payoff; rather he refuses to pay because enough others in the group do not pay that he would suffer a net cost if he did.[22]

Echoing Olson's pronouncement that, absent coercion, individuals will not act for their common benefit, Hardin's game theory model shows that voluntary participation makes collective action much less likely.

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[20] Wade, 101.
[21] Russell Hardin, "Collective Action as an Agreeable n-Prisoner's Dilemma," *Behavioral Science* 16 (1971): 473-4.
[22] Ibid., 476.

Challenges to Standard Models

The three models discussed above provide the foundation upon which the theory of CPRs has been built. While each of these models addresses the collective action problem CPRs share with public goods provision, the fact that CPRs are neither pure public goods nor pure private goods invariably leads to complications in the application of these models. We now turn to the critiques, theoretical and empirical, of these models.

The free-rider problem has remained one of the cornerstones of collective action analysis, largely due to the power of the logic argument articulated by Olson. According to Isaac and Walker (1988), most literature on the provision of public goods "focuses on the problems associated with the underrevelation of demand and the relationship of such 'free-riding' behavior to variation in group size."[23] Isaac and Walker set up a laboratory experiment to test the relationship between group size and the provision of public goods under varying group sizes and individual marginal returns from contribution. The authors find experimental support for the standard group size argument when "that distinction in group size is driven by reductions in the marginal per capita return to an individual' but no distinct effect from the actual number of participants.[24] Further, the study found that the level of marginal private contribution return (MPCR) has a significant effect on behavior, regardless of the fact that the experiment was designed so that the MPCR level did not affect the player's dominant strategy of zero contribution.[25] While this research does not fundamentally contradict the predictions of the free-rider

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[23] R. Mark Isaac and James M. Walker, "Group Size Effects in Public Goods Provision: The Voluntary Contributions Mechanism," *The Quarterly Journal of Economics* 103 (1988): 179.
[24] Ibid., 180.
[25] Ibid., 196-7.

problem, and in fact reinforces its conclusion in cases where an increase in the number of participants leads to a reduction of MPCR, it does indicate that group size alone may not be a sufficient condition for free-rider behavior to emerge in a collective action problem. When group size reduces MPCR and the perceived marginal effect of an individual's action on the group decision, this research supports the group size hypothesis. However, group size increases absent a concomitant decline in MPCR does not appear to increase free riding.

In addition to general critiques and empirical tests of the three aforementioned models, specific challenges to these theories have arisen in the context of CPR management. Robert Wade acknowledges that "much of the pessimism about the practical viability of collection action in the use of common-pool resources stems" from these three theories.[26] However, due to the unique characteristics of CPRs as quasi-public goods, this pessimism, and the subsequent policy prescriptions of privatization or state regulation, is often misguided.[27]

Wade argues that the key assumptions of the static Prisoner's Dilemma game result in a more pessimistic conclusion than less restrictive models and empirical evidence would suggest. By relaxing the assumption that the game is played only once, game theorists have shown that the chances of a cooperative equilibrium increase.[28] In particular, a trigger strategy can be adopted, wherein a player begins by cooperating and threatens to stop cooperating if another player defects. Furthermore, if players are able to negotiate rule changes, then they will be able to impose incentives for cooperation.

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[26] Wade, 97.
[27] Ibid.
[28] Ibid., 98.

Within the specific context of an Indian village, Wade finds that CPRs are modeled more accurately as repeated games in which the appropriators do have some institutional-level control over the rules that govern the resource. Furthermore, the likelihood of undetected free riding is relatively low, increasing the prospect for cooperation and collective action.[29]

Wade likewise finds that the application of the "tragedy of the commons" model to CPRs makes critical assumptions about the state of the nature of the resource and the interaction between the resource and the appropriator. Hardin "assumes that the individual herder has no information about the aggregate state of the commons."[30] As a result of this ignorance of the state of the world, the individual herder's exploitation of the resources leads to is degradation. While such an assumption may be reasonable in certain dispersed CPRs, it does not make sense in the context of many such resources. Just as Wade's assumption of the ability to change the institutional structure allowed for the monitoring of cheating, many CPRs are characterized by relatively easy monitoring of the condition of the commons.[31]

Wade's studies of institutions for the management of CPRs in Indian villages contradict the prediction of Olson's collective action problem. Olson's model accounts for cooperation through selective incentives and non-cooperation through the free-rider problem. However, Wade finds that positive coercion is almost completely lacking and punishment is nominally present but weak. Wade finds that it is not coercion, nor selective benefits, that determine whether or not an individual will cooperate, but rather

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[29] Ibid., 99.
[30] Ibid., 100.
[31] Ibid.

whether the net collective benefit is sufficiently high.[32] Contrary to the prediction that coercion or private benefits are necessary to encourage collective action, Wade finds that individuals tend to make decisions based on the level of benefit to the group. As a result of these findings, Wade proposes that self-governed collective action is possible given the common-pool resource meets certain conditions. These conditions will be discussed in greater detail in the next chapter.

Additional critiques of the applicability of these models to common-pool resource problems acknowledge that, while many CPR problems are prisoner's dilemmas, this is far from the only game theoretic model that can fit particular situations. Gardner et al. show that, within the game theoretic framework, additional structures, including Chicken and Assurance games can characterize common-pool resource problems.[33] These games, though similar in structure to Prisoner's Dilemma, exhibit different incentive structures, and therefore, different outcomes for a collective action problem. The game of Chicken, in which "the consequences of nobody doing the work are so disastrous" that either player would act unilaterally to provide the good, makes provision problems of CPRs much less likely. In contrast, an Assurance game is characterized as neither player's contribution is sufficient for provision, so players prefer either that both contribute or that neither contributes.[34] Gardner et al. outline the broad variables that can be used to analyze CPRs and show that proper classification of the CPR dilemma is central to understanding what game structure is being used and what policy recommendations will work.

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[32] Ibid., 102.

[33] Roy Gardner, Elinor Ostrom, and James M. Walker, "The Nature of Common-Pool Resource Problems," *Rationality and Society* 2 (1990): 338.

[34] Ibid., 339.

Empirical Evidence

Further empirical evidence has called into question the pessimistic outcomes of the classical models. As such, the standard policy recommendations of privatization or state regulation often neglect the possibility of successful collective action and self-governance of a CPR. Before turning to the literature on a theoretical framework to understand this higher propensity to cooperate, several historical examples of self-governance are discussed.

In *Governing the Commons*, Elinor Ostrom provides a thorough overview of the empirical evidence and fieldwork that set the stage for the transformation in the theoretical models used to analyze common-pool resources. Ostrom shows that the traditional model and their pessimistic predictions on the prospect of collective action do not account for the emergence of resource management institutions in certain circumstances. At the time, there was no theoretical foundation to explain why some CPRs achieve efficiency while others do not.[35] Ostrom discusses the two fundamental challenges facing a common-pool resource: appropriation problems and provision problems. An appropriation problem is one concerned with the effect of allocation methods on the net return to appropriators, while provision problems concern the effect of the assignment of building and maintaining the resource system. Ostrom notes that the appropriation problem is not a Prisoner's Dilemma in the case of a limit-access CPR, and that the provision problem is, itself, a second order collective action problem.[36]

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[35] Ostrom, *Governing the Commons*, 40.

[36] Ibid., 46-9. A second order collective action problem is one in which participants have an incentive to free ride on the provision of a mechanism to solve the first order collective action problem the provision of a public good.

The fieldwork of Ostrom and others presented in *Governing the Commons* laid the foundation for the conceptual and rigorous theoretical modeling of the conditions for collective action in common-pool resources. Common-pool resources like the forests of Torbel, Switzerland, the Yamanoka villages in Japan, and irrigation systems throughout Spain and the Philippines all exhibit self-governance. It is important to note that these common property systems have existed for centuries and are not mere historical holdovers. As the forests of Switzerland indicate, both private and communal ownership have existed in a country or region for centuries. Furthermore, the Swiss cases demonstrate that private and communal ownership have been used to fit specific resource systems. For example, agricultural land is privately owned while meadows, forests, and wastelands are common property. The Swiss villages manage the common-pool resource through access, appropriation, maintenance, and monitoring rules decided upon by the appropriators themselves.[37]

In the case of the Swiss communal forests, the rules for the harvesting of timber illustrate how appropriation, monitoring, and maintenance rules can be used to produce a relatively efficient outcome while keeping monitoring costs low. Since timber can only be harvested at a designated time each year known to all participants, monitoring of the rule is easily enforced. Furthermore, by imposing a set time for harvesting determined by the village forester, the condition of the commons can be monitored, reducing the likelihood of reaching a tragedy of the commons situation. Teams of eligible households do the harvesting. The harvest is then divided into approximately equal stacks based on

[37] Ibid., 63-5.

the number of eligible households and a lottery is used to assign each household a stack.[38] Although the specific rules governing the Japanese forest commons differ from those adopted in Switzerland, appropriators likewise adopted rules to manage the resource.

Ostrom has studied self-governing irrigation systems in both *Governing the Commons* and subsequent articles. In a 1993 article with Roy Gardner on irrigation systems in Nepal, the authors formulate a game between headenders and tailenders of an irrigation system to show that, in the absence of an institutional mechanism that can be used to bargain over the rules of the game, equilibrium production will be less than optimal. Specifically, Ostrom and Gardner find that in the state of nature game (without the bargaining mechanism) using a simple water production function, the spatial disparity between headenders and tailenders results in headenders supplying 0.14 units of labor and tailenders supplying 0.02 units of labor, leading to water production of only 0.5 units. By contrast, the system optimum is for the headenders and tailenders to each supply 1 unit of labor, resulting in 4 units of water being produced. [39] Ostrom and Gardner sketch out a potential water-for-labor bargain for the rules of allocation that headenders and tailenders could reach. Their hypothesis is that the difference in water allocation between headenders and tailenders will be reduced in a system in which the appropriators have the ability to bargain. However, several common asymmetries in CPRs may alter the relative distribution of bargaining power. For example, in an irrigation system, permanent headworks will favor headenders because it reduces the labor required to maintain the system. The distributional advantage to headenders may be offset by mutual dependence

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[38] Ibid., 65.
[39] Ostrom and Gardner (1993), 98.

if the labor of tailenders is necessary to maintaining the system.[40] If this is the case, the bargains will be relatively symmetric and the system is more likely to approach an efficient outcome. Ostrom and Gardner propose two possible rotation rules "to transform the state of nature game into a game with a symmetric bargaining solution."[41]

Ostrom and Gardner examined irrigation systems in Nepal to test their hypothesis that self-governed irrigation systems are more likely than externally managed systems to produce an equitable allocation of water. They ran a regression of "water availability difference" on the length of the canal system, the labor input, whether the system has permanent headworks, the presence of canal linings, whether the system is self-governed, and whether the system is in the Terai region.[42] The authors find that self-governance does significantly reduce the allocation difference between headenders and tailenders.[43] Ostrom and Gardner's findings are particularly significant because they offer empirical evidence that the collective action problem can be overcome in CPRs. They show that, given circumstances that produce relatively symmetric bargaining, external management and state regulation of CPRs can, in fact, reduce the likelihood of efficient outcomes.

This empirical evidence not only called into question the application of traditional collective action models to common-pools, it demonstrated that state regulation, far from being the 'only' policy solution save privatization, could actually lead to less efficient allocation. As a result of the empirical work outlined above and many other studies with similar findings, the theory of CPRs required significant reexamination. The theory grew

[40] This mutual dependence outcome is analogous to the aforementioned Assurance game.
[41] Ostrom and Gardner (1993), 99-100.
[42] The Terai region is flatter and more fertile than other regions in the study. The authors argue that physical asymmetries are easier to deal with in the Terai than elsewhere.
[43] Ostrom and Gardner (1993), 103-4.

out of the qualitative observations of the characteristics of successful common-pool resources documented by Ostrom and Wade, among others. But the transformative shift in CPR theory came from the application of cooperative game theory to such problems.

Cooperative Game Theory

Before discussing the possibility of cooperative equilibria in the context of common-pool resource problems, it will be helpful to discuss earlier work in the context of infinitely and finitely repeated Prisoner's Dilemma games. While these models are not entirely analogous to a CPR game, they nonetheless provide a foundation on which to discuss theoretical explanations for cooperation.

Robert Axelrod discusses the emergence of cooperation in the context of an infinitely repeated Prisoner's Dilemma game. Axelrod argues that one of the most important factors in the emergence of a cooperative equilibrium is that the 'shadow of the future is long. In other words, the players anticipate future interactions and do not view it as a one-shot game.[44] As Axelrod shows, the likelihood of a cooperative strategy being played is directly tied to a player's discount factor. To show that a cooperative equilibrium can emerge among rational egoists under an infinite/uncertain time horizon, Axelrod proves, using evolutionary game theory, that tit-for-tat is a collectively stable strategy.[45] A collectively stable strategy is a strategy that cannot be invaded by any other strategy. A strategy (1) is said to invade another strategy (2) if the expected payoff of (1)

[44] Robert Axelrod, "The Emergence of Cooperation Among Egoists," *The American Political Science Review* 75 (1981): 312.
[45] Tit-for-tat refers to a player's strategy of beginnings by cooperating and then playing whatever action the opponent played in the preceding round.

playing against (2) is greater than the expected payoff of (2) playing against (2).[46] The implications of Axelrod's findings are that cooperation can emerge in a Prisoner's Dilemma among rational actors through the adoption of a trigger strategy, tit-for-tat, assuming that the discount factors are sufficiently high and that the time horizon is infinite or uncertain.

Kreps et al. extend this framework to show that, given certain informational asymmetries, a cooperative equilibrium can emerge even in a finitely repeated Prisoner's Dilemma.[47] The central argument of Kreps et al. is that, while it has been extensively shown that the Nash equilibrium strategy of defect prevails through backward induction in finitely repeated Prisoner's Dilemma games with complete information, in the presence of asymmetric information regarding a player's reputation, cooperation will be maintained in all but the last few rounds. This result stems from the uncertainty about whether or not the opposing player is tit-for-tat. Kreps et al. show that, as long as it is not common knowledge that one player is not tit-for-tat, cooperation will persist until the final few rounds.[48]

While the article by Axelrod and Kreps et al. show the a sustained cooperative equilibrium is achievable under certain conditions in a Prisoner's Dilemma game, scholars, including Gardner et al., have shown that CPRs cannot always be characterized as Prisoner's Dilemmas. As such, Ostrom et al. develop a class of games to represent the

[46] Axelrod (1981): 310-1.
[47] David M Kreps, et al., "Rational Cooperation in the Finitely Repeated Prisoner's Dilemma," *Journal of Economic Theory* 27 (1982): 245-252.
[48] Ibid., 248-50.

common-pool resource problem.[49] Extensions of this model are subsequently analyzed using evolutionary game theory to show that a cooperative equilibrium can emerge in a CPR and illustrate what factors are likely to affect this equilibrium.

The common-pool resource class of games outlined by Ostrom et al. is characterized as one in which an individual's utility depends on the population's total endowment invested in the common-pool resource, as well as the individual's proportional benefit from the aggregate investment in the CPR. They show that the equilibrium outcome in the absence of communication or sanctioning results in overinvesting in the resource just as the Prisoner's Dilemma predicts. Ostrom et al. conduct an experiment in which participants play a finite-horizon CPR game under varying levels of communication and sanctioning in the event that a player deviates from the optimal level of contribution. The authors find that the ability to communicate (craft covenants) and impose an internal sanctioning mechanism allows participants to make credible commitments and achieve a more efficient collective payoff than predicted by the traditional models. Furthermore, those subjects who adopted sanctions when given the opportunity to communicate and design a sanctioning mechanism reached an average net yield of 90% after the cost of fines and fees, compared to 56% for subjects who did not adopt any mechanism. Additionally, the defection rate was 38% higher in the latter case. The fact that participants are able to impose a covenant and sanctions provides

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[49] Elinor Ostrom, James Walker, and Roy Gardner, "Covenants With and Without a Sword: Self-Governance is Possible," *American Political Science Review* 86 (1992): 404-17.

experimental evidence not merely that a cooperative equilibrium can emerge, but also that self-governance of a CPR is a viable alternative to state regulation.[50]

The model developed by Ostrom et al. is explored in an evolutionary game theory context and interpreted in light of the emerging emphasis on social norms in common-pool resource management by Sethi and Somanathan. The authors point to relatively low sanction costs of defections compared to the individual benefit from noncompliance as an indicator that it is not merely a monetary cost that deters defection, but rather a violation of social norms that reinforces compliance. Sethi and Somanathan develop an evolutionary game to show why it is possible for social norms to endure in a common-pool resource despite pressure for noncompliance. In their evolutionary model, the authors show that "whenever there is a stable noncooperative equilibrium…with a positive resource stock, then there exists a *cooperative* equilibrium with a *higher* stock level."[51] However, a noncooperative equilibrium can always be stable while a cooperative equilibrium can be stable only under specific conditions. The implications of this conclusion are particularly significant for determining whether or not CPR management will be successful or not. First, if a noncooperative equilibrium arises it is likely to persist. Second, the fact that a cooperative equilibrium is not always stable makes it particularly dependent on initial conditions. In this case, Sethi and Somanathan show that parameter shocks can result in the depletion of a resource that was previously characterized by prolonged restrained use.[52]

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[50] Ibid., 414.
[51] Rajiv Sethi and E. Somanathan, "The Evolution of Social Norms in Common Property Resource Use," *The American Economic Review* 86 (1996): 769. Emphasis original.
[52] Ibid., 766-9.

The emphasis on social norms, a variable not historically considered in the literature on collective action and common-pool resources, coupled with the emergence of evolutionary game theory models for such problems, has helped to reconcile the disparity between the pessimistic predictions of traditional collective action theory and the overwhelming empirical evidence to show that cooperative outcomes can emerge. One of the main disconnects between theory and practice in the realm of collective action, according to Elinor Ostrom, is the fact that while experimental results have upheld rational egoist behavior in a market setting, the predicted behavior does not hold in collective action experiments. In fact, numerous public good experiments have shown that participants contribute 40-60 percent of their endowments, despite the fact that zero contribution is the strictly dominant strategy. Various contextual factors affect the contribution rate in public goods experiments, including "the framing of the situation and rules for assigning participants, increasing competition among them, allowing communication, authorizing sanctioning mechanism, or allocating benefits."[53]

Ostrom argues that the evolutionary game theory model of collective action not only allows for a cooperative outcome but more fundamentally for variation of player type in the group. While traditional theory assumes only rational egoists, the evolutionary approach includes players who are predisposed to follow a social norm. Therefore, the equilibrium becomes a function of the distribution of player types and what information players have about each other's type. For example, in the case of complete information regarding type, cooperative players will consistently receive a

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[53] Elinor Ostrom, "Collective Action and the Evolution of Social Norms," *The Journal of Economic Perspectives* 14 (2000): 139-41.

higher payoff than rational egoists. However, in the case of a large population with no type information, the rational egoist type will prevail.[54]

Ostrom's claim that player type variation exists within a population is, in fact, supported by experimental economics research. A study by Fehr and Gächter finds that "altruistic punishment" took place frequently in a public goods game. Altruistic punishment is defined as punishment of defectors despite costs to the punisher and a lack of material gain. The punishment of defectors itself constitutes a second order public good because no individual has an incentive to punish defection but the whole group would benefit from punishment. The presence of altruistic punishment solves this second order public good problem.[55] Fehr and Gächter's findings of the prevalence of altruistic punishment support Ostrom's claim that a variety of player types can be present in a population. This assumption of type variation, confirmed through experimental evidence of altruistic punishment, is fundamental to the theory presented in the next chapter to explain cooperation in CPRs.

Numerous empirical studies and emerging evidence from experimental economics have dispelled the notion that the only solutions to a common-pool resource problem are privatization or state regulation. This evidence called into question the applicability of the standard theories of collective action and catalyzed the theoretical framework of evolutionary game theory and the importance of social norms in governing common-pool

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[54] Ibid., 145-9.

[55] Ernst Fehr and Simon Gächter, "Altruistic Punishment in Humans," *Nature* 415 (2002): 137. This notion of altruistic punishment is contrasted with reciprocal altruism because altruistic punishment occurs when repeated interaction is not expected to take place. An altruistic punisher does not punish so as to encourage future cooperation because the punisher will not receive the benefit of future cooperation.

resources. The next chapter discusses, qualitatively and quantitatively, the theory of common-pool resources.

CHAPTER 3

THEORY

This chapter discusses the theory of common-pool resources both qualitatively and quantitatively. The design principles of successful common-pool resources are central to understanding why the traditional theories of collective action, outlined in the previous chapter, fail to predict the outcomes observed in common-pool resources.[1] Additional contextual variables that may affect the success or failure of the regime are discussed before turning to the mathematical model.

The history of common-pool resource theory demonstrates that a strictly economic analysis based on the rational actor model, without taking into account social and institutional factors, does not adequately predict the prevalence of cooperation in common-pool resource situations. As such, in order to clarify the role of social norms in the context of the evolutionary game theory model, it is necessary to discuss the design principles found in successful common-pool resources regimes. These design principles give an insight into what parameters are instrumental in producing a cooperative equilibrium.

The seven design principles that characterize successful common-pool resource systems are: (1) clearly defined boundaries, (2) compatibility between appropriation and

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[1] Many of these design principles are outlined in Ostrom's *Governing the Commons*.

provision rules and local conditions, (3) collective-choice arrangements, (4) monitoring, (5) graduated sanctions, (6) conflict-resolution mechanisms, and (7) minimal recognition of rights to organize.[2]

The first principle, a clearly defined boundary, applies to both the resource itself and to the appropriators allowed access. A clearly defined boundary transforms a resource system from open-access to limited access. This subtle distinction has ramification for the exploitation of the resource.[3] In addition to mitigating the exploitation problem that arises under open access, a clearly defined boundary serves an important role in developing the social norms that promote cooperation. The boundary reduces uncertainty by defining relationships and establishing with whom to cooperate.[4]

The reasoning behind the compatibility of rules and local conditions is straightforward. A rule that is not adapted to the specific context of the resource with respect to such variables as the appropriation quantity, timing, or permissible technology will create a perception of unfairness in the system, reducing the chances of cooperation. This is one reason why, in the context of rules and social norms, external management and enforcement may not produce an optimal outcome. An allocation policy imposed by an external agency is less likely to address the unique circumstances of that resource system than one designed by the people who use it. Furthermore, external management will tend to render social norms less effective by reducing the weight of or eliminating the non-monetary sanctions that participants often impose. This also reduces the ability

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[2] Ostrom (1990), 90.

[3] For a derivation and explanation of this distinction, see Gordon (1954).

[4] Ostrom (2000), 149.

of participants to signal their propensity to cooperate through the adoption of a system of rules.

The third principle, that appropriators have access to a collective choice mechanism, follows from the second. A rule that is compatible with the local conditions requires knowledge of the state of the resource. The presence of a collective choice mechanism not only increases the likelihood of perceived equitable distribution, it also allows for relationships to build among appropriators and for more direct communication. As mentioned in the previous chapter, direct communication tends to increase the likelihood of an efficient outcome.[5]

The fourth and fifth design principles, monitoring and graduated sanctions, are central to transforming the game from a tragedy of the commons/free-rider problem into one in which cooperation can actually emerge. Within the evolutionary context, these mechanisms serve as assurance for the 'conditional cooperator' type of player. This player is one whose cooperation hinges upon the assumption that most other players will not defect.

Changes in, or the absence of these mechanisms could indicate a decline in the strength of an resource system. Several factors may affect the stability of an equilibrium. These include in-migration, changes in technology, state regulation, international aid, changes in prices, the vitality of the resource to the appropriators.[6] Another parameter that is proposed to influence the stability of an equilibrium is the dispersion of the common-pool resource. The theory is that, as the dispersion of the resource increases, monitoring becomes more costly, direct communication among appropriators becomes

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[5] Ostrom et al. (1992), 413-4.
[6] Ostrom, (2000), 153-4.

less likely, and social norms become more heterogeneous. All of these are expected to decrease the likelihood of a stable, cooperative equilibrium emerging. One focus of this study is to examine this hypothesis.

With this conceptual theory of common-pool resources extrapolated, the game theory model can now be developed. This analysis is based on the common-pool resource game developed by Ostrom et al. (1992) and follows the formulation of the game outlined by Sethi and Somanathan (1996).

A static common-pool resource game is one in which each individual's appropriation from the resource (i.e. fishing effort or the quantity of water used in an irrigation system), x_i, helps determine the total appropriation from the resource. The aggregate appropriation is denoted $X=\Sigma x_i$. The aggregate yield of the resource is a function of the aggregate appropriation, X, and the stock of the resource, K, which is assumed to be a constant. The aggregate yield function is denoted f(X) and it is a standard increasing and concave production function.[7] The opportunity cost, *a*, of some other good is assumed to be constant for all individuals in the community. Therefore, the total cost to the community of appropriation from the resource is *a*X. Assuming that each individual's share of the total benefit, f(X), is directly proportional to her level of appropriation, x_i, each individual's payoff, π_I, is given by

$$\pi_i(x_i, \dots, x_n) = (x_i/X)*f(X) - ax_i .$$

Aggregate payoff, Π, is given by

$$\Pi(x_i, \dots, x_n) = \Sigma\pi_I = f(X) - aX$$

[7] Sethi and Somanathan (1996), 770.

The efficient level of aggregate appropriation, X_E, is the appropriation level for which Π is maximized,

$$f'(X) = a.^{8} \qquad (3.1)$$

At the efficient level of aggregate appropriation, the marginal product of the approrpiation in the resource is equal to the opportunity cost, *a*. However, due to the non-excludable nature of common-pool resources, a feature they share with public goods, an individual makes his decision based on the average product, not the marginal product. Since each appropriator's payoff is based on the aggregate level of appropriation from the resource, X, each additional unit of appropriation will change the appropriator's payoff proportional to the aggregate level. Therefore, the payoffs must be rewritten in terms of average product, A(X) = f(X)/X. An individual's payoff can now be written as

$$\pi_I(x_i, X) = x_i(A(X) - a). \qquad (3.2)$$

Similarly, the aggregate payoff becomes

$$\Pi = X(A(X) - a). \qquad (3.3)$$

Under open access, in which there is no limit on the number of appropriators, each individual maximizes her payoff by appropriating to the point that the average product equals the opportunity cost, *a*. However, in a limited-access common-pool resource, overexploitation will occur, but it will not reach the point of A(X) = *a*. For each individual, the additional rent from appropriating an additional unit is given by A(X) – *a*, while the loss is only X*A(X)/n, compared to the collective loss of X*A(X).[9] This situation is exactly what is predicted by the tragedy of the commons. The common-pool

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[8] Ibid.
[9] Ibid., 771.

resource game has a unique Nash equilibrium in which all players appropriate x_N, more than the efficient amount in the resource.

While the static game predicts an inefficient outcome, the empirical studies discussed in the previous chapter show that this is often not the case. However, the imposition of sanctions alone is not enough to alter this equilibrium. The reasoning is as follows. Sanctioning turns the static game discussed above into a two-stage game. The first stage is identical to the one just described, but in the second stage players decide whether or not to punish those who invested more than the efficient amount. Assuming that the punishment involves a cost to both the punisher and the person being punished, no player will be made better off by punishing in the second round of the game. No player will punish and the subgame perfect equilibrium is for each player to invest at the original Nash equilibrium level and not punish any of the other players. Therefore, the mere imposition of sanctions will not affect the equilibrium outcome of the game.

The aforementioned model assumes that all of the players are purely rational egoists. When this condition is relaxed to include different types of players who adopt different strategies, evolutionary dynamics can be shown to lead to outcomes other than the subgame perfect equilibrium predicted above. A key distinction of evolutionary game theory is that, while it does not explicitly reject the notion of rational egoist actors, it does allow for variation in the strategy profiles players employ.[10] This does not mean that actors do not respond to incentives or do not seek to maximize payoffs. It simply means that, contrary to many standard game theory models that assume all actors are

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[10] This assumption of variation in player type is reasonable in light of experimental economics research to support altruistic behavior in public goods games. See Fehr and Gächter (2002) for evidence of such altruistic behavior.

rational and self-interested, the evolutionary approach allows for players to be programmed to play other pure strategies. Thus, the game does select for strategies that yield higher payoffs than the population average. Evolutionary game dynamics are rational in that players pass on strategies that return a higher than average payoff.[11] A cooperative equilibrium can even be shown to emerge, providing a theoretical explanation of the overwhelming empirical evidence to support the emergence of cooperation in collective action problems.

Assume that there are only two appropriation levels, a high extraction, x_h, and a low extraction, x_l, and three types of players: enforcers, who play x_l and sanction those who don't; cooperators, who play x_l but do not sanction those who don't; and defectors who play x_h.[12] The unique subgame perfect equilibrium of this game is defection and no sanctioning, just as was shown above.[13] However, taking into account the different types of players, the payoffs for each type can be rewritten to reflect their appropriation levels and sanctioning. Let π_c denote cooperators, π_d denote defectors, and π_e for enforcers. (Note: This payoff is different from the payoff in the static game for the efficient aggregate appropriation.)

$$\pi_c = x_l(A(X) - a) \quad (3.4)$$
$$\pi_d = x_h(A(X) - a) - s_e\delta n \quad (3.5)$$
$$\pi_e = \pi_c - s_d\gamma n \quad (3.6)$$

[11] It is generally assumed that strategies breed true. However, in the case of the CPR game model, instead of assuming that the set of strategies used in the population chances only through generational transfer, players are able to adapt their strategy through learning if they observe that another strategy is earning a higher-than-average payoff.
[12] Enforcers in this game are analogous to the altruistic punishers discussed by Fehr and Gächter (2002).
[13] Sethi and Somanathan (1996), 772.

In the above equations, s_d and s_e refer to the proportion of defectors and enforcers in the population, respectively. The parameters δ and γ refer to the cost of punishment to defectors and enforcers, respectively.

These modified payoffs indicate that defectors do not have an unambiguously higher payoff. While their investment level is higher, if the sanction meted out by enforcers is large enough, their payoff will not necessarily be higher than cooperators. However, unless there are no defectors in the population, cooperators will have higher payoffs than enforcers. Therefore, the cooperator strategy weakly dominates the enforcer strategy.[14]

Given the payoff differentials between the strategies, evolutionary pressure will move the population toward those strategies with higher payoffs. One model of this type of evolutionary pressure is replicator dynamics, in which "the rate of growth of the share of the population using a strategy is proportional to the amount by which that strategy's payoff exceeds the average payoff of the strategies in the population."[15] These dynamics can be represented as a system of ordinary differential equation.

To derive these differential equations, define the number of players in the population using strategy *i* at time *t*, p_i, in relation to the whole population, p, at time *t*. Call this proportion s_i. A simple algebraic manipulation gives the equation $p*s_i=p_i$. Taking the first derivative with respect to time gives the following equation[16]

$$\dot{p}s_i + p_i\dot{s}_i = \dot{p}_i \qquad (3.7)$$

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[14] Ibid., 773.
[15] Ibid.
[16] To simplify notation the *t*'s have been taken out of the equations. These equations are still functions of time. The dots represent a first derivative.

The growth rate of each strategy in the population will be proportional to the difference between that strategy's payoff, π_i, and the average payoff, $\bar{\pi}$.[17] Therefore, the replicator dynamics can be described by the following system of equations

$$\dot{s}_i = s_i(\pi_i - \bar{\pi}) \qquad i\text{=c,d,e} \qquad (3.8)$$

Since the proportion of players using each strategy in the population must sum to one, the system can be written as a system of two differential equations.

$$\dot{s}_i = s_i(\pi_i - \bar{\pi}) \qquad i\text{=c,d} \qquad (3.9)$$

The population average payoff can be written in terms of s_c and s_d based on the aforementioned property of the sum of the proportions. This average payoff becomes

$$\bar{\pi} = s_c\pi_c + s_d\pi_d + (1 - s_c - s_d)\pi_e.^{18} \qquad (3.10)$$

While traditional game theory models are primarily concerned with equilibrium states, the population dynamics of the evolutionary model make it necessary to address the stability of such equilibria. Stability in a dynamical system refers to the path of a solution to the system as time progresses. Formally,

> a stable equilibrium point is one such that for each neighborhood U of the point there exists a neighborhood U_1 of the point contained in U such that starting from a state in U_1 the state of the dynamical system will never leave U. An *asymptotically stable* equilibrium is one which is stable and has a neighborhood such that, starting in the neighborhood, the state of the system will converge to the equilibrium in the long run.[19]

In order for a system to be in equilibrium, all of the strategies present must earn equal payoffs. This follows intuitively from the definition of the replicator dynamics. As stated above, the replicator dynamics relate the growth rate of a strategy *i* in the

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[17] For an in-depth discussion of replicator dynamics, see Weibull (1995) and Taylor and Jonker (1978).
[18] Ibid., 774.
[19] Ibid., Emphasis original.

population to the extent to which its payoff exceeds the average for the population. Any payoff differential would cause the share of strategy *i* to increase or decrease. Clearly, such a state could not be in equilibrium.

Given this definition of a stationary equilibrium in an evolutionary game, we can discuss intuitively what possible equilibria exist. Since enforcers do strictly worse than cooperators in the presence of defectors due to sanctioning costs, a point containing all three strategies cannot be in equilibrium. Similarly, a point with only cooperators and defectors cannot be in equilibrium because defectors will earn higher payoffs from their higher level of investment without being sanctioned due to the absence of enforcers. The only two equilibria that are stable are one consisting entirely of defectors, the *D* equilibrium, and one consisting of cooperators and enforcers, the *C-E* equilibrium. In order to show the stability of these two equilibrium points formally, we need to examine the properties of the Jacobian matrix for the dynamical system described in (9).[20] The general form of a Jacobian is given by

$$\mathbf{J} = \begin{pmatrix} \partial \dot{s}_c / \partial s_c & \partial \dot{s}_c / \partial s_d \\ \partial \dot{s}_d / \partial s_c & d\dot{s}_d / \partial s_d \end{pmatrix}.$$

Only defectors are present in the *D* equilibrium, so $\pi_c = \pi_e = 0$ and. Therefore, the Jacobian becomes

$$\mathbf{J} = \begin{pmatrix} \pi_c - \bar{\pi} + s_c(\partial(\pi_c - \bar{\pi}) / \partial s_c) & s_c(\partial(\pi_c - \bar{\pi}) / \partial s_d) \\ s_d(\partial(\pi_d - \bar{\pi}) / \partial s_c) & \pi_d - \bar{\pi} + s_d(\partial(\pi_d - \bar{\pi}) / \partial s_d) \end{pmatrix}$$

By taking these first partial derivatives and simplifying, we find that the Jacobian becomes

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[20] A Jacobian matrix is a matrix of all first-order partial derivatives for a system of equations.

$$\mathbf{J} = \begin{pmatrix} -(x_h - x_l)(A(nx_h) - w) & 0 \\ -\gamma n & -(x_h - x_l)(A(nx_h - w) - \gamma n \end{pmatrix}.^{21}$$

Since the appropriators of a limited-access CPR still earn positive rents ($A(nx_h > w$) and $x_h > x_l$, the element J_{11} will be negative. J_{12} will be 0 because s_c is zero in the *D* equilibrium. J_{21} becomes $-\gamma n$ by taking the derivative, substituting (3.10) for $\bar{\pi}$. Since the cost of sanctioning, γ, and n, the number of appropriators, must both be positive, element J_{21} must be negative. Based on the same reasoning using for J_{11} and J_{21}, element J_{22} must also be negative. This means that

$$\det\mathbf{J} = (-(x_h - x_l)(A(nx_h) - w)(-(x_h - x_l)(A(nx_h) - w) - \gamma n) - 0(-\gamma n) > 0$$

and

$$\text{trace}\mathbf{J} = J_{11} + J_{22} = (-(x_h - x_l)(A(nx_h) - w) + (-(x_h - x_l)(A(nx_h) - w) - \gamma n) < 0.$$

A positive determinant and negative trace of the Jacobian matrix are necessary and sufficient conditions for local asymptotic stability.[22] Therefore, the *D* equilibrium is asymptotically stable for all initial parameter values.

The proof of stability for the *C-E* equilibrium follows the same formulation as the above proof of stability in the *D* equilibrium. However, this stability depends on the size of the sanctioning penalty to defectors, δ. Specifically, if $\delta n > (x_h - x_l)(A(nx_l) - w)$, then the *C-E* equilibrium is asymptotically stable.[23] This result is quite important because it means that the initial conditions are a determining factor in which equilibrium will emerge. While the *D* equilibrium is asymptotically stable for all parameter values, the *C-*

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21 Sethi and Somanathan (1996), 783-4.
22 Ibid., 783-4.
23 Ibid., 774. The proof follows the same steps as outlined in the above proof. For a complete proof, see Sethi and Somanathan (1996).

E equilibrium is only asymptotically stable given a high enough sanctioning penalty to defectors. Furthermore, if a temporary parameter shock shifts moves the system away from the *C-E* equilibrium, it can still result in a permanent move to the *D* equilibrium because this equilibrium is stable for all parameter values.

The fact that there are two stable equilibria, including the latter in which players are guided by norms to use the resource efficiently, provides a theoretical framework to support the empirical evidence that collective action can be achieved in a common-pool resource. Furthermore, it indicates that the initial conditions of the system are significant in determining which equilibrium will emerge.[24] As the evolutionary dynamics predict, a sufficiently high level of sanctioning should produce a stable cooperative equilibrium. Central to effective sanctioning is monitoring of appropriators' use of the resource. As it becomes less likely that appropriation levels are monitored, more and more users have an incentive to overexploit the resource. While this notion is generally captured in the collective action literature through the group size effect, this study hypothesizes that low population density increases the costs of monitoring, decreasing the likelihood of sanctioning, thereby encouraging defector behavior. This study seeks to test the effects of sanctioning and population density on cooperation within the context of irrigation systems in Nepal. The next chapter presents an overview of the history of irrigation in Nepal before turning to the empirical analysis.

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[24] Ibid., 774-5.

CHAPTER 4

OVERVIEW OF IRRIGATION IN NEPAL

While irrigation systems are interesting case studies in collective action problems and self-organization, in Nepal's case understanding the successes and failures of irrigation systems is paramount to its economic development. This provides both an impetus for practical research in common-pool resource management and a wealth of data and information on irrigation systems and institutions. The country's abundant water resources, coupled with the primacy of agriculture in its economy, make the efficient allocation of water a key step in poverty alleviation, modernization, and economic growth. The substantial shortcomings in these areas, as well as the evidence on irrigation inefficiency, point to widespread institutional factors that limit the efficiency of water use. Such inefficiencies have led to substantial funding increases for irrigation systems and a renewed focus on local management. These policy changes have provided some natural experiments that have allowed researchers to identify some of the significant factors in the success and failures of common-pool resource institutions. Before turning to these characteristics of CPRs, an overview of Nepalese irrigation will be presented, followed by a discussion of several case studies.

The importance of water resources to the Nepalese economy can hardly be overstated. Nepal, a nation of 28 million in South Asia, remains a largely rural population, with only 17 percent of the population living in urban centers.[1] This, coupled with the push for economic development, makes water resources and management central to the Nepalese government's concern. In terms of water resources, Nepal is the second richest country in the world, containing 2.27 percent of the world's water resources.[2] Despite these abundant water resources, fertile land, and hydroelectric power potential, the quality of life remains low and poverty and unemployment remain high.[3] Given the abundance of resources and the funding that been committed to irrigation projects of the decades, Nepal's irrigation sector would be expected to substantially outstrip its current performance. However, agricultural data indicates that Nepal's irrigation systems consistently under perform relative to natural endowment and funding. All of these factors point to the need for a new approach to water management in Nepal.

Agriculture's importance in the national economy makes irrigation central to economic growth. Moreover, given technological and land constraints, coupled with the fact that nearly all arable land in Nepal is currently cultivated, irrigation will be central to future agricultural development.[4] Agriculture is Nepal's single largest sector, accounting for 38 percent of GDP as of 2006.[5] Furthermore, investment in agriculture accounts for 12-15 percent of gross domestic investment.[6] With agriculture making up such a significant portion of Nepal's economy, productivity becomes a major consideration. But the productivity statistics raise serious questions about the infrastructure and management

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[1] *The World Factbook 2009*. Washington, D.C.: Central Intelligence Agency, 2009.
[2] Kiran Prasad Bhatta, et al., "Performance of agency-managed and farmer-managed irrigation systems: A comparative case study at Chitwan, Nepal," *Irrigation and Drainage Systems* 20 (2005): 179.
[3] Som Nath Poudel, "Water Resources Utilisation: Irrigation," in *The Nepal-India Water Relationship: Challenges*, D.N. Dhungel and S.B. Pun, eds., (Springer, 2009), 99.
[4] Ibid., 105.
[5] Ashok Raj Regmi, "Self-Governance in Farmer-Managed Irrigation Systems in Nepal," *Journal of Developments in Sustainable Agriculture* 3 (2008): 20.
[6] Poudel, 104.

of irrigation in the country. Productivity falls well short of expectations given the country's natural resources. While 85 percent of the 2.6 million hectares of cultivated area has the potential for irrigation, only 42 percent of this land has irrigation infrastructure.[7] Furthermore, less than 20 percent of the 2.2 million hectares of land that could be irrigated receive year-round irrigation.[8] 900,000 hectares are irrigated by surface water and 200,000 hectares are irrigated by groundwater.[9]

Most of the groundwater irrigation occurs in Terai, a flat and fertile area located in southern Nepal near India. In addition to Terai, irrigation mostly occurs in the hills and the river-valleys. Compared to Terai, physical asymmetries like steep or undulating terrain tend to be more pronounced in the hills and river-valleys.[10] These asymmetries are likely to favor the headenders of the system who can draw water to their fields before farmers at the tail have a chance to withdraw any. Such physical challenges provide one possible explanation for the poor performance of irrigation systems.[11]

However, these physical asymmetries are only one contributing factor in the dismal performance of Nepalese irrigation systems. A combination or institutional, physical, and technological variables have been posited to explain the poor performance of irrigation systems. Regmi cites weak governance and enforcement, unrealistic productivity projections, a lack of user participation, and a misunderstanding of farmer priorities as reasons for the failures of Nepalese irrigation systems.[12] Poudel identifies unexpected flooding and landslides damaging irrigation structures, a lack of maintenance,

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[7] Regmi, 21.
[8] Ibid., 20.
[9] Ibid., 21.
[10] Ostrom and Gardner, 101.
[11] In their analysis of water availability in irrigation systems, Ostrom and Gardner (1993) find that whether the system was in Terai was significant at the 90 percent level.
[12] Regmi, 22.

and poor coordination between farmers and agencies as the key challenges to the sector.[13] Given the centrality of agriculture in Nepal's economy, the productivity shortfalls are of considerable concern to policymakers. To combat these challenges, the Nepalese government and the Department of Irrigation (DOI) have enacted a variety of policies over the last half-century to build new large-scale irrigation systems, improve infrastructure, advance technology available to farmers, and, more recently, emphasize local involvement and management.

Significant funding has been poured into the irrigation sector by both government agencies and external donors since the middle of the 20th century. It is estimated that $1.2 billion US was spent on the irrigation sector between 1956 and 2000. Of that, the Nepalese government funded 20 percent, with the remaining 80 percent coming from external donors like the Asian Development Bank and the World Bank.[14] Prior to the early 1950s, irrigation was almost exclusively a local concern. However, after the early 1950s, the Nepalese government became actively involved in irrigation development. Its focus was primarily on the construction of "large-scale agency-managed irrigation systems (AMIS)."[15] In fact, approximately 60 percent of the estimated $1.2 billion has been spent on new irrigation infrastructure.[16]

The construction of such large-scale AMIS represents a substantial shift in the makeup of irrigation in Nepal. Only after 1956 did central planning of irrigation development occur through the government's five-year plans. Prior to the government's

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[13] Poudel, 105.
[14] Regmi, 22.
[15] Wai Fung Lam, "Improving the Performance of Small-Scale Irrigation Systems: The Effects of Technological Investments and Governance Structure on Irrigation Performance in Nepal," *World Development* 24 (1996): 1302.
[16] Regmi, 22.

intervention, most irrigation systems were small-scale and locally managed by the farmers who used them. It should be noted that to this day farmer-managed irrigation systems (FMIS) account for 75 percent of irrigation, while 25 percent is AMIS.[17] Between 1956 and 1980, irrigation development focused almost entirely on the construction of large-scale infrastructure projects. Eventually, policy emphasis shifted toward expanding and repairing existing infrastructure. However, even during this time government officials conducted almost all planning, construction, maintenance and management without the involvement of the farmers actually using the system.[18]

Despite the substantial investment in new, large-scale irrigation systems, their performance has been disappointing. Large-scale projects like Sunsari-Morang, Bagamti, and Narayani have supplied far lower water volumes than originally planned while frequently having capital cost over-runs. In fact, the Bagamti project reportedly cost $5,000/hectare to construct.[19] Furthermore, in recent years the proportion of the irrigation budget indirectly spent on overhead has skyrocketed from 15 percent to nearly 50 percent.[20] Several case studies from the Chitwan region have underscored the "unsatisfactory performance of public sector irrigation schemes" noting that despite the high investment in public irrigation development, these AMIS regularly under perform compared to FMIS.[21]

An example of the counter-intentional outcomes of replacing local institutions with new, large-scale irrigation infrastructure can be seen in the Chiregad Irrigation Project in Dang funded by USAID. An area that was previously irrigated by five separate

[17] Regmi, 21.
[18] Ibid.
[19] Regmi, 22.
[20] Poudel, 106.
[21] Bhatta et al., 179.

FMIS was served instead by a single new irrigation system boasting permanent headworks and cement-lined canals[22]. In addition, the DOI appointed an entirely new user committee that did not carry over water managers from any of the five FMIS. Whereas prior to the conversion all five of the villages served by the system consistently received water, after the DOI-constructed AMIS began operating, only three of the five villages consistently received water.[23]

The Chiregad Project is but one example of that represents a common result of government intervention in irrigation systems. A similar outcome occurred in the Kodku Irrigation System in the Lalitpur District. The Kodku system was constructed and historically operated by the farmers who used it. As of 1988 its operating area was estimated at 560 hectares and was served by the Khotku Khola River. The system featured unlined canals and a temporary headworks composed of mud and branches. Repair of the headworks had to be performed frequently due to the river's varying water flow and frequent change of course. In 1965 the Department of Irrigation, Hydrology, and Meteorology (later the DOI) constructed a permanent headworks, lined part of the main canal, and assumed operation and maintenance duties for the system. As with the Chiregad Project, the technical improvements to the Kodku system actually decreased the level of water in the system. In fact, after the DOI began managing the system it became quite difficult for farmers at the middle and tail of the system to extract adequate water.[24] The Chiregad Project and Kodku System are not outliers among government intervention

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[22] Ostrom and Gardner (1993) and Lam (1996) both find that the presence of a permanent headworks tends to reduce the efficiency of water allocation in an irrigation system.
[23] Regmi, 22.
[24] Lam, 1302.

cases, but rather represent a widespread result that has been documented in numerous case studies.[25]

The fact that the irrigation system became less efficient despite technological advances indicates that physical capital alone is not the determining factor in the success of an irrigation system. Social capital and local institutions that have been built up through years of interaction must also play a part in water allocation. The shift from farmer management to government management was accompanied by government officials applying uniform rules across the board despite the diversity of circumstances faced by individual farmers and systems.[26] By failing to recognize the importance of local institutions and instead employing a standardized approach to management of irrigation systems, the Nepalese government was hindering its own efforts to improve water allocation efficiency.

A shift in irrigation policy occurred around 1985, after which the Nepalese government began to place more emphasis on the involvement of the system's users. As outlined in the *Water Resource Act 1992* and subsequently in the *Irrigation Policy 2003*, the DOI set out policy goals to develop FMIS and transfer those systems constructed by the DOI to the control of water-users associations (WUAs). The policy explicitly sets out to encourage user participation in government-led irrigation development. Despite this policy objective to reinvest in FMIS, the DOI has only invested about 16 percent of funds toward this goal.[27]

All this points to the ineffectiveness of solely technical or financial solutions and suggests that a failure to recognize the importance of institutional factors may be

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[25] For a list of several of these case studies, see Lam (1996), p. 1303.
[26] Ibid.
[27] Regmi, 21-2.

hindering the performance of irrigation systems. As the case studies presented above demonstrate, contrary to the conventional wisdom of addressing collective action problems, government intervention is not necessarily an effective solution to common-pool resource problems. In fact, to the extent that government intervention alters the social capital and institutions of a localized resource allocation mechanism, the technical improvements that may allow for greater water delivery, namely a permanent headworks and lined canals, are often more than offset by decreases in allocation efficiency due to changes in the organization structure that affect the likelihood of cooperation among appropriators. While the policy shift in the mid-1980s may be a step in the right direction in its emphasis on user participation, several studies indicate that the reinvestment and technological improvements alone will not enhance performance when they alter the local institutions and social norms that govern FMIS.[28] However, determining which social, physical, and institutional factors affect the efficiency of allocation is necessary to crafting effective policy. Using data collected from over one hundred Nepalese irrigation systems, this paper will seek to ascertain which of these characteristics are significant in the efficient allocation of water.

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[28] Ostrom and Gardner (1993), Lam (1996), and Regmi (2008) all show that FMIS tend to outperform AMIS even though AMIS have had substantially more capital investment.

CHAPTER 5

DATA AND METHODOLOGY

Outside of a controlled experimental setting, the prospect of quantifying cooperation becomes increasingly difficult due to physical, environmental, institutional, and social factors. Given the challenges of empirically measuring the emergence of a cooperative equilibrium, it is not a trivial matter to quantify the performance of an irrigation system. Determining a metric that accurately represents the performance of an irrigation system, particularly from an institutional perspective without ignoring physical and environmental factors, in a manner that can be standardized across systems, is itself a challenge. These difficulties help account for the prevalence of case studies and laboratory experiments in the common-pool resource literature. While these two approaches have proven quite fruitful, the development of an accurate irrigation system performance measure has expanded the range of empirical research that can be done. Wai Fung Lam has developed three dimensions of irrigation performance: physical, delivery, and productivity. Each of these three dimensions is a composite of several variables. The physical dimension constitutes the status of the system's physical structures and the "short-run economic technical efficiency."[1] The delivery dimension is comprised of water adequacy, water distribution equity, and the reliability of the water

[1] Wai Fung Lam, "Improving the Performance of Small-Scale Irrigation Systems: The Effects of Technological Investments and Governance Structure on Irrigation Performance in Nepal," *World Development* 24 (1996): 1312.

supply. The productivity dimension is made up of agricultural product per hectare per year, head-end cropping intensity, and tail-end cropping intensity.[2] For the purposes of measuring irrigation system performance in this analysis, the delivery dimension will be used, particularly a measure of the relative availability of water at the head and tail of the system.

Data Set and Sources

In order to empirically test the conditions that lead to a cooperative equilibrium in a common-pool resource, a combination of physical and institutional variables must be analyzed. All of the variables used in the regression come from the Nepal Irrigation Institutions and Systems Database (NIIS), a database of institutional and physical variables for irrigation systems compiled from fieldwork in Nepal conducted by the Workshop in Political Theory and Policy Analysis at Indiana University in Bloomington.[3] The variables used in the analysis include the dependent variable, *WAD*, and the independent variables: *popden*, *sanct*, *typeirr*, *headwork*, *whobuilt*, and *terrain*.

Dependent Variable

The water availability difference (*WAD*) will be used as the dependent variable in this analysis because it most directly addresses the question of cooperation while allowing for the physical asymmetries inherent in an irrigation system to be taken into account. A system in which a cooperative equilibrium has emerged would be characterized by a water availability difference between headenders and tailenders that is zero or close to it. While it should be noted that natural physical factors like cracks in a

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[2] Ibid. 1305, 1312.

[3] I would like to express my deepest gratitude to the Workshop in Political Theory and Policy Analysis and Julie England for allowing me to access their database to complete my analysis.

canal could still produce a positive *WAD* even when headenders do not overexploit the resource, the *WAD* nonetheless remains an effective measure of appropriator behavior in an irrigation system because it measures the extent to which appropriators in the advantageous position at the head of the system restrain their use, allowing appropriators at the tail to draw more water than would be predicted by a rational actor model.

WAD is derived from the difference in the water available at the head and tail of an irrigation system averaged over the spring, monsoon, and winter seasons.[4] This is calculated by adding the differences between the head and tail in each of the three seasons then dividing by three. For the purposes of this analysis, the availability of water is measured on a scale of three possible values: adequate, limited, and scarce or nonexistent.[5] The NIIS provides a definition for each of these values. Water supply is said to be adequate when it is available to all users and appropriators are confident of its supply. Limited refers to the case in which there is frequently some water stress and water must be distributed carefully in order to plant all fields. Scarce or nonexistent water availability occurs when only part of the area is planted due to lack of water. In order to calculate the difference in water availability, adequate, limited, and scarce are coded 2, 1, and 0, respectively.

Since the *WAD* is calculated from a categorical variable that qualitatively measures water availability averaged over three seasons, it can only take on discrete integer and non-integer values on the interval [-2, 2]. For example, a score of -2 would mean that, in each of the three seasons, the tail of the system received adequate water

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[4] The *WAD* is calculated as an average over three seasons to compensate for the physical differences in water available during a monsoon season and a dry season.

[5] This method of coding the water availability follows the format used by Ostrom and Gardner (1993), which also uses the NIIS database.

while the head received scarce water. Similarly, a score of 0.33 would mean that, in one season, the tail received scarce water while the head received limited water, or that the tail received limited water while the head received adequate water. A score of 0 would mean that, in each of the three seasons, the head and tail of the system received the same level of water. This indicates that the *WAD*, as initially calculated, is not a continuous variable and not likely to have a normal distribution. A Jarque-Bera test to check the normality of *WAD* returned a Jarque-Bera statistic of 673.6991 with a sample size of 255. Compared to the critical value Chi-square with two degrees of freedom, 5.99, the Jarque-Bera statistic indicates that the null hypothesis of normal distribution is rejected. As such, a limited dependent variable regression model will have to be used to analyze the data.

While the *WAD* can take on only discrete integer and non-integer values, the fact that they are derived from categorical measures of water availability means that they can be mapped to integer values so long as the order remains unchanged.[6] Due to the limited number of observations, it is not possible to perform a multinomial logit regression with six dependent variable categories to correspond to differing levels of cooperation.[7] The DV can be converted to a binomial variable to represent 'altruistic' behavior versus 'opportunistic' behavior. Any value of *WAD* less than or equal to zero is coded as zero, while any value greater than zero is coded as 1. Zero represents to altruistic behavior on

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[6] It is easy to see that the magnitude does, in fact, correspond to different levels of cooperation. For example, a *WAD* of 0.33 would mean that there was a difference in the availability of water of one in one season. A *WAD* of 0.67 would mean that there was either a difference of two in one season or a difference of one in two seasons.

[7] For the regression with the *sanct* IV, the number of observations is 191. For the regression with the *fines* IV, the number of observations is 173.

the part of the headenders and a *WAD* of one refers to any level of opportunistic behavior on the part of the headenders.

Independent Variables

The independent variables used in the regression encompass physical, social, and institutional factors in irrigation systems. These variables and their expected effects on *WAD*, and therefore on the emergence of cooperation in a common-pool resource, will be discussed. Table 5.1 presents the descriptive statistics for the independent variables.

TABLE 5.1

DESCRIPTIVE STATISTICS FOR INDEPENDENT VARIABLES

Variable	Mean	Median	Std. Dev.	Min	Max
popden	2.4225	1.57233	3.351	0.00353	31.875
sanct	1.4293	1	1.31549	0	4
typeirr	0.90576	1	0.29293	0	1
headwork	0.39791	0	0.49075	0	1
whobuilt	0.20419	0	0.40417	0	1
terrain	0.5235	1	0.50076	0	1

The variable *popden* measures the population density of the irrigation system, is measured as the number of appropriators who use the system divided by the number of hectares irrigated by the system. The two components used to compute this variable both measure the size of the system, albeit in qualitatively different ways. As such, in order to understand the expected effect of population density on the water availability difference, it is necessary to first understand these two measures. The standard theory of collective action holds that free-rider behavior increases with group size due to monitoring difficulties and the likelihood of being pivotal in the provision of a public good decreases.[8] Group size would be expected to increase the probability of observing a

[8] Olson (1965), 48.

WAD score of 1. However, previous empirical studies on common-pool resources have shown no correlation between size and collective action.[9] The theory of the evolution of social norms in CPRs, as outlined in Chapter 3, indicates that monitoring may be instrumental in the emergence of a cooperative equilibrium. The mean population density is 2.42 appropriators per hectare. The median population density is 1.57 appropriators per hectare. A high population density is expected to make monitoring easier by increasing the likelihood of free riding being detected. Therefore, increasing *popden* is expected to decrease the probability of observing a *WAD* score of 1.

The sanctioning of appropriators who overexploit the resource is shown in the evolutionary game theory model to be the key parameter in determining whether or not a cooperative equilibrium will emerge. In order to test the effect of sanctioning on *WAD*, the independent variable, *sanct*, was constructed as an ordinal variable for the likelihood of sanctioning in the system. The possible values range from 0 to 4. 'Very unlikely' sanctioning is coded 0. 'Unlikely' sanctioning is coded 1. 'Likely as not' sanctioning is coded 2, while 'Likely' is coded 3. 'Very likely' sanctioning is coded as 4. The mean is 1.4293, indicating that the odds of getting sanctioned are well below 50 percent (coded as 2). Furthermore, the median value of 1 confirms that the value of the sanctioning variable tends to be small. While this variable does not exactly measure the cost of the sanction to the defector, it does serve as a proxy for the level of sanctioning in the system. Theory predicts that a higher level of sanctioning would reduce the probability of observing a *WAD* score of 1.

Another variable that was considered to represent sanctioning was *fines*. In contrast to *sanct*, this variable represents the level of fine an appropriator receives for

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[9] Regmi (2008), 25. Regmi also cites the findings of Tang (1992), Lam (1998), and Ternström (2002).

breaking a system rule. Like *sanct*, this is an ordinal variable. For the purposes of analysis it is coded as follows: 0=no fine; 1=light fine; 2=moderate fine; 3=heavy fine. The anticipated effect of *fines* on *WAD* is identical to the reasoning discussed above for the sanctioning variable.[10]

The institutional variable for the type of irrigation management present in a system addresses the question of whether or not it is possible for efficient allocation of a common resource to arise without either public ownership or privatization. While the traditional theory or common resources predicts a dire outcome of overexploitation, empirical evidence suggests that self-governance is possible. Ostrom and Gardner argue that farmer-managed irrigation systems (FMIS) are more likely to reduce the water availability difference between the head and tail of a system than agency-managed irrigation systems (AMIS) because FMIS are able to bargain over operational rules for the system, increasing the likelihood of tailenders interests being considered. In their analysis, they find that whether a system is farmer managed is negatively correlated with the difference in water availability, and that this result was significant at the 95 percent level.[11] The variable *typeirr* is a dummy variable coded as 0 if the system management involves a government agency and 1 if solely farmers manage it. The mean value for this variable is 0.91. This means that many of the systems used in this analysis are farmer managed. This is not surprising considering that approximately 75 percent of all Nepalese irrigation systems are farmer managed. Therefore, *typeirr* would be expected to reduce the probability of observing a *WAD* score of 1.

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[10] A parallel regression was conducted with the variable *fines* in place of sanct. This variable does not alter the significance of a sanctioning variable in the regression. The results of the regression can be found in the appendix.

[11] Ostrom and Gardner (1993), 103-4.

The presence of a permanent headworks in an system is considered a sign of technologically advanced modern irrigation and is generally assumed to increase the efficiency of the system. Whereas a temporary headworks must be rebuilt regularly by the appropriators of the system, a permanent headworks reduces the required labor to be put toward system maintenance. While this may be expected to increase the efficiency of the system, Ostrom and Gardner argue that a permanent headworks increases the relative bargaining power of the headenders because they are no longer dependent on the labor supplied by tailenders to maintain the system. As such, despite the technical gains of a permanent headworks, it will actually reduce the cooperation between headenders and tailenders.[12] In this regression, the variable *headwork* is a dummy variable coded as 0 if a temporary headworks is present and 1 if a permanent headworks is present in the system. The mean for *headwork* is 0.39791. This indicates that approximately 40 percent of systems have a permanent headwork. The predicted effect of *headwork* on water availability difference is expected to be positive. That is, when *headwork* is 1 the probability of observing a *WAD* of 1 increases.

The history of irrigation in Nepal underscores that a major shift occurred in around the middle of the 20th century as the government invested in the development of large-scale irrigation systems. As the cases presented in Chapter 3 show, such infrastructure projects often resulted in decreased efficiency despite the technical advances that came with government construction. This indicates that who constructed the system may be significant in predicting whether or not a cooperative outcome will emerge. Systems constructed by farmers are generally smaller and tend to maintain local institutions and self-governance that promote social norms that can lead to cooperative

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[12] Ibid., 103.

behavior. Systems constructed by outsiders, by contrast, are often amalgams constructed from several smaller systems. Therefore, a system constructed by a group other than the farmers who actually use it is likely to lack the social norms and institutions that are expected to encourage cooperation. The variable *whobuilt* is a dummy variable coded 0 if built by farmers and 1 if built by either the government or a non-governmental agency. The mean for *whobuilt* is 0.20419, meaning that approximately 20 percent of systems were built by either the government or a non-governmental agency. A system built by either the government or a non-governmental agency is expected to increase the probability of observing a *WAD* score of 1, corresponding to an opportunistic outcome.

In order to account for the unique geographical characteristics of Nepal, the terrain in which the irrigation system is located must be taken into account. Ostrom and Gardner argue that physical asymmetries that favor headenders are expected to be more pronounced in areas where the terrain is steep or undulating. By contrast, the plains region of Terai in southern Nepal is expected to reduce the physical asymmetries that allow headenders on the first plateau to withdraw most of the water before it reaches subsequent plateaus.[13] The diminished physical asymmetries in Terai suggest that distributional advantages of the headenders are mitigated in this region, reducing their ability to over-appropriate from the system. To take into account the impact of terrain on the difference in water availability, the dummy variable *terrain* is coded 0 if the irrigation system is not located in Terai and 1 if it is. The mean of 0.5235 shows that approximately half of the systems used in this study are located in Terai. As Ostrom and Gardner's analysis suggests, if the system is in Terai it is expected to reduce the probability of observing an opportunistic outcome in the availability of water.

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[13] Ostrom and Gardner (1993), 101-3.

Empirical Model

Given that the dependent variable is coded dichotomous to describe whether or not altruistic behavior is taking place, a logit regression model is used to test the impact of the aforementioned independent variables on the difference in water availability. The empirical model for a logit regression with the independent variables listed above is given in equation 1 below.

$$P(WAD = 1) = \frac{1}{1 + e^{-(b_1 popden + b_2 sanct + b_3 typeirr + b_4 headwork + b_5 whobuilt + b_6 terrain)}} \quad (1)$$

The results of this regression model will be discussed in the next chapter.

CHAPTER 6

RESULTS AND CONCLUSION

This chapter presents the results of the logistic regression model discussed in the previous chapter and its impact on the hypothesized relationships between the independent variables and the observance of cooperative behavior in an irrigation system. The results will be discussed in the context of theories to explain cooperation and in relation to previous empirical findings. Shortcomings and limitations of the model will be discussed as well as the context of these results within the common-pool resource literature. Finally, possible future research to address the questions raised by these results will be discussed.

The empirical model used in this study seeks to determine the effect of various physical, institutional, and social variables on the probability of observing altruistic or opportunistic behavior in an irrigation system. Specifically, this analysis tests the impact of population density and sanctioning on the difference in water available at the head and tail of a system. Before turning to a discussion of the results of the regression, it is necessary to test for multicollinearity among the independent variables. Table 6.1 presents the correlation matrix for the independent variables *popden*, *sanct*, *typeirr*, *headwork*, *whobuilt*, and *terrain*.

TABLE 6.1

CORRELATION MATRIX FOR INDEPENDENT VARIABLES

	popden	sanct	typeirr	headwork	whobuilt	terrain
popden	1					
sanct	0.1117	1				
typeirr	-0.2287	-0.0174	1			
headwork	0.0269	-0.0785	-0.3602	1		
whobuilt	0.0768	0.0223	-0.5034	0.4373	1	
terrain	-0.1615	-0.2232	0.0152	0.0687	0.0411	1

As Table 6.1 shows, there is a relatively strong negative correlation (-0.5034) between *typeirr* and *whobuilt*. This correlation is not surprising. *Typeirr* is a dummy variable coded as 0 if system management involves a government agency and 1 if farmers manage it. *Whobuilt* is a dummy variable coded 0 if built by farmers and 1 if either the government or a non-governmental agency built it. The history of irrigation in Nepal discussed in Chapter 4 details irrigation policy in the 20th century characterized by investment in the construction of large-scale irrigation systems subsequently managed by government agencies. While there has been a policy shift toward farmer management, this is a relatively recent development. As such, it is reasonable to assume that many of the systems financed by outside agencies maintain the agency management structure. Given that this correlation is near the lower bound threshold for multicollinearity and that it is not logical to combine these two dummy variables, the model will still include both variables, bearing in mind that it could depress the statistical significance of variables in the model. With this caveat, the results of the logit regression can now be presented and discussed.

Table 6.2 displays the results of the logistic regression, presented as coefficients for the independent variables. In order to understand the impact of a given independent variable, however, it is necessary to look at the marginal effects of the regression. The marginal effects are given in Table 6.3 below.

TABLE 6.2

LOGISTIC REGRESSION RESULTS

Logistic Regression		Obs	191
		LR chi^2 (6)	14.13
log likelihood	-114.74105	Prob >chi^2	0.0283
		Pseudo R^2	0.058

wad	Coef.	Std. Err.	z	P>lzl
popden	-0.0274137	0.0489909	-0.56	0.576
sanct	-0.1106834	0.1272716	-0.87	0.384
typeirr	-1.219636	0.6434085	-1.9	0.058
headwork	0.0984739	0.3700042	0.27	0.79
whobuilt	0.5433708	0.4596052	1.18	0.237
terrain	-0.5614206	0.3325081	-1.69	0.091

TABLE 6.3

MARGINAL EFFECTS FOR LOGISTIC REGRESSION

Marginal effects after logit

Variable	dy/dx	Std. Err.	z	P>lzl
popden	-0.006046	0.01081	-0.56	0.576
sanct	-0.024411	0.02806	-0.87	0.384
typeirr	-0.2925369	0.15329	-1.91	0.056
headwork	0.0217899	0.08211	0.27	0.791
whobuilt	0.1253026	0.1094	1.15	0.252
terrain	-0.1238424	0.07285	-1.7	0.089

Table 6.2 shows the results of the logistic regression. This model was run with 191 observations. The LR chi-square (6) is the likelihood ratio chi-square test. It is calculated from the starting and ending log likelihood. Since there are six independent variables in the regression, this statistic has six degrees of freedom. The LR chi-square (6) is used to test if the overall model is significant. The Prob > chi-square is the probability of obtaining an LR chi-square statistic of 14.13 under the null hypothesis that

all the independent variables are not significantly different from zero. A value of 0.0283 indicates that the null hypothesis is rejected at the 95 percent confidence level. Thus, the model does have some explanatory power and some of the independent variables should be significantly different from zero. A statistic equivalent to the R^2 in an OLS regression does not exist for logistic regression so a variety of pseudo-R^2 statistics have been developed to measure goodness-of-fit.[1] The interpretation of the pseudo-R^2 is not entirely analogous to the interpretation of the R^2 in an OLS regression. If multiple regressions were done with the same data set, the pseudo-R^2 statistics could be compared to give an idea of which model is a better fit. Even though it is difficult to conclusively interpret the meaning of a 0.058 pseudo-R^2 in the same way a similar value would be interpreted in an OLS regression, this value is somewhat low. Combined with the insignificance of many of the independent variables and limited explanatory power of the significant variables, this model likely suffers from an omitted variable problem. This problem and possible remedies will be discussed in greater detail later in the chapter.

The significance of the variables and their effects on the difference in water availability can now be discussed. Tables 6.2 and 6.3 report the coefficients and marginal effects (dy/dx) of the variables, respectively. When discussing the significance of variables the p-values in Table 6.2 will be reported. In order to understand the effects of a variable on the likelihood of observing cooperative or non-cooperative behavior, however, it is more intuitive to discuss the marginal effects.

Of the six independent variables in the model, two are significant at the 90 percent level. The variable *typeirr* has a p-value of 0.058 and the variable *terrain* has a

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[1] The McFadden pseudo-R^2 is reported in this regression.

p-value of 0.091. None of the other variables are significant even at the 80 percent level. Neither population density nor sanctions, the two variables discussed in Chapter 3, are found to be significant.[2] The lack of significance for population density is comparable to previous studies that found no correlation between size and collective action.[3] Regmi (2008) finds no correlation between group size and collective action.[4] Furthermore, experiments on group size and the provision of public goods have shown that merely increasing the size of the group may not be sufficient to increase free riding. Rather, when group size increases lead to a decline in a participant's marginal private contribution return (MPCR), free riding does tend to increase.[5] Without accounting for MPCR in the irrigation systems data, it is not possible to discern whether this study supports the conclusion that size alone accounts for the lack of correlation between population density or group size and defection. While this study does call into question one of the most widely-cited implications of the theory of collective action, that free riding or defection tends to increase as the size of the group increases due to difficulty of monitoring, further study on group size effects is necessary.

The sanctioning variable is not significant in this regression either. However, this finding should be considered preliminary for several reasons. First, the nature of the variable used to represent sanctioning is an ordinal variable coded from zero to four for increasing likelihood of sanctioning. Therefore, the variable used in this regression does not explicitly quantify the size of the sanction. A similar regression using the sanctioning

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[2] A parallel regression conducted using a similar sanctioning variable, *fines*, was conducted. The results of this regression are presented in an appendix.
[3] The regression was also conducted using group size instead of population density. Group size was not found to be significant either.
[4] Regmi (2008), 25.
[5] Isaac and Walker (1988), 196.

variable *fines*, in which *fines* is coded from zero to three for increasing size of sanction, is presented in the appendix. This regression returns similar results and does not alter the lack of significance. While the *fines* regression does support the findings of the regression presented above, the limited descriptive range of the variable means that further tests should be done. A variable that would represent fines monetarily could help confirm whether or not sanctioning has any effect. Second, experimental evidence indicates that participants in a public goods game do, in fact, contribute "in accordance with the group norm" in order to avoid punishment.[6] Further experimental and field research is needed to reconcile these contradictory results.

Both the type of irrigation management system and the location of the system in Nepal are significant at the 90 percent level in this regression. The marginal effects in Table 6.3 give the effect that a variable has on the probability of observing a *WAD*=1. Both variables have negative effects on the probability of observing a non-cooperative outcome of unequal water availability, as predicted. The marginal effect for *typeirr* is -0.2925. Recall that *typeirr* is a dummy variable coded 0 if the irrigation system management involves an agency (AMIS) and 1 if the farmers manage the system (FMIS). The marginal effect of -0.2925 indicates that the difference in probability for a non-cooperative outcome (*WAD*=1) emerging with FMIS (*typeirr*=1) and AMIS (*typeirr*=0) is -0.2925. This means that agency management increases the probability of non-cooperative behavior by 0.2925. Both theory and previous research predict this to be the case. The theoretical reasoning is as follows. From an institutional perspective, a FMIS allows the appropriators to bargain over the operational rules of the system. By contrast,

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[6] Fehr and Gächter (2002), 139.

an AMIS does not generally allow for bargaining over management and appropriation rules. The presence of operational level bargaining increases the likelihood that the considerations of the tailenders will be taken into account. Thus, an FMIS is more likely to produce a cooperative equilibrium. These results support earlier findings by Ostrom and Gardner (1993). In their analysis of irrigation systems in Nepal, the authors find that farmer management is significant at the 95 percent level, and that there is a negative relationship (-0.32) between the water availability difference and whether the system is farmer-managed.[7] In the context of their analysis, the presence of farmer management reduces the difference in water available by 0.32 units. Since the present study uses a logistic regression, the results of these two studies cannot be directly compared numerically. However, the type of management system is significant in both cases and both seem to have a substantial impact on the emergence of cooperative behavior in an irrigation system.

The marginal effect for *terrain* is -0.1238. This variable is coded 0 if the irrigation system is not located in the plains region of Terai in southern Nepal, and 1 if it is in Terai. The interpretation of this marginal effect is analogous to that of the type of irrigation system. The difference in the probability of a non-cooperative outcome emerging in Terai (*terrain*=1) and not in Terai (*terrain*=0) is -0.1238. This means that a system's location in the plains region reduces the probability of a non-cooperative outcome by 0.1238. This fits with the predicted result that, because physical asymmetries between the head and tail of the system are easier to deal with in Terai, the difference in water availability will be closer to zero. These results are also supported by the 1993

[7] Ostrom and Gardner (1993), 103-4.

study by Ostrom and Gardner. The authors find that the location of the system was significant at the 90 percent level and that a negative relationship (-0.10) existed between location and the water availability difference.[8]

The type of irrigation system and the location of the system combine to reduce the probability of reaching a non-competitive outcome by 0.4163. While this probability indicates that other variables that would affect cooperation are missing from the model, these variables certainly strengthen the explanatory power of the model. The large magnitudes of the marginal effects of both the type of irrigation system and location of the system further support the theoretical arguments and previous empirical results that farmer management and the terrain significantly affect cooperation in Nepalese irrigation systems.

Neither the presence of a permanent headworks (*headwork*) nor whether the system was farmer-built (*whobuilt*) were significant in this regression. A permanent headworks, a staple of modern irrigation technology, has been hypothesized to actually increase water availability difference by reducing the bargaining power of tailenders who relied on the dependence of headenders on the labor supply of the tail to rebuild the headworks every year. Previous studies by Ostrom and Gardner found that the presence of a permanent headworks had a positive impact on water availability difference, significant at the 95 percent level.[9] These conflicting results call into question the importance of physical variables in irrigation system management. Further studies must be conducted with a larger sample size to determine whether or not the presence of a permanent headworks is significantly related to cooperative behavior.

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[8] Ostrom and Gardner (1993), 103.
[9] Ibid., 103.

The lack of significance in some of the variables, the low pseudo-R^2, and the limited ability of significant variables to account for the probability of a non-cooperative outcome all point to model specification issues. Particularly, the model presented above likely suffers from an omitted variable problem, wherein a significant explanatory variable has been omitted from the regression. Further studies must be conducted to determine what variable(s) are missing from this analysis.

Several possible physical, institutional, and social variables must be studied in order to improve the model. Physical variables include the length of the system and presence of a lined canal. The length of the system would be expected to increase monitoring costs, making free riding easier and increasing the probability of defection. The presence of a lined canal would be expected to reduce leaks that can affect the water available at the tail regardless of the actions taken by the head. Institutional variables that define the collective choice mechanisms present in a system may also be significant. For example, the presence of an institutional mechanism in which appropriators can make covenants and establish threats of sanctions may, in fact, be sufficient to encourage cooperative behavior regardless of the size or likelihood of sanctioning. The existence of credible threats and the ability of appropriators to communicate prior to extracting from the resource could explain the high levels of cooperation and lack of significance of sanctioning. Social variables may also play a major role in development of norm-guided behavior in the realm of common-pool resource appropriation. Social cohesion is expected to increase the likelihood of cooperating. Therefore, measures of social cohesion should be tested in this model. Possible variables include but are not limited to religious homogeneity, ethnic identity, and in-migration into the region. All of these could affect the social norms present in the system, altering the prospect for cooperative behavior.

An additional weakness that should be addressed in subsequent research is the question of time-dependent cooperation. The computation of the dependent variable is initially averaged over three seasons to smooth the water availability difference in an attempt to control for particularly wet or dry seasons. While this certainly has its advantages, it also has potential drawbacks for the explanatory power of the model. Specifically, by averaging the data over three seasons time-dependent cooperation and defection may be ignored. In periods of abundance like a monsoon season, appropriators at the head may be more inclined to behave altruistically because they are not constrained by water scarcity. By contrast, in a drier season appropriators at the head of a system may be far less willing to restrain their own use for the sake of tailenders in the face of water scarcity. To test the robustness of cooperative behavior, it is necessary to test the time dependency of cooperation. In order to properly do so, data must be collected and analyzed over many more seasons.

This study presents an empirical analysis of the determinants of cooperative behavior in irrigation systems in Nepal. Within the context of the common-pool resource literature, the results presented in this chapter serve several purposes. First, these results confirm the importance of institutional and physical variables, specifically the type of irrigation system and its location within Nepal, as explanatory variables in the emergence of cooperation. Second, the results further call into question the relationship between group size and free riding. The lack of significance is far from a definitive rejection of the logic of collective action, but the lack of significance of population density indicates that there is not a strong relationship between difficulty monitoring (i.e. low population density) and non-cooperative behavior. The group size hypothesis may still hold explanatory power insofar as it corresponds to declining private revenue, but a free riding outcome following from lack of monitoring does not seem to be the driving force behind a relationship between size and cooperation. Third, these results expand the application of empirical analysis to sanctioning in a field setting and not a lab. While these results do not fit with the experimental economics results and should be considered merely preliminary due to the nature of the data, to entirely dismiss these findings would be premature. Even though the severity of sanctions may prove significant in a laboratory setting, the interrelationship between human propensity to sanction defection and the role of institutions as a forum to make credible threats of sanctions and covenants over proper allocation may diminish the need for sanctions in light of social norms. While further research must be conducted on both sanctioning and the role of institutions in the management of a common-pool resource, these results continue to indicate that social norms may play a more significant role than previously thought in common-pool resource problems.

APPENDIX A

LOGIT REGRESSION RESULTS FOR INDEPENDENT VARIABLE FINES

logit wad popden fines typeirr headwork whobuilt terrain

```
Iteration 0:  log likelihood =  -111.01811
Iteration 1:  log likelihood =  -102.50561
Iteration 2:  log likelihood =  -102.48228
Iteration 3:  log likelihood =  -102.48227
```

```
Logistic regression                     Number of obs   =        173
                                        LR chi2(   6)   =      17.07
                                        Prob > chi2     =     0.0090
Log likelihood =  -102.48227            Pseudo R2       =     0.0769
```

wad	Coef.	Std. Err.	z	P>lzl	[95% Conf.	Interval]
popden	-.0544289	.0540914	-1.01	0.314	-.1604462	.0515884
fines	.0229373	.2140999	0.11	0.915	-.3966908	.4425654
typeirr	-1.666921	.7533591	-2.21	0.027	-3.143478	-.1903644
headwork	.2096073	.3768809	0.56	0.578	-.5290658	.9482803
whobuilt	.5673585	.4785051	1.19	0.236	-.3704944	1.505211
terrain	-.437649	.3479378	-1.26	0.208	-1.119595	.2442966
_cons	.9650799	.8537528	1.13	0.258	-.7082449	2.638405

Marginal effects after logit
y = Pr(wad) (predict)
= .33547665

variable	dy/dx	Std. Err.	z	P>lzl	[95% C.I.	]	X
popden	-.0121339	.01208	-1.00	0.315	-.035816	.011548	2.41597
fines	.0051135	.04773	0.11	0.915	-.088437	.098664	1.34104
typeirr*	-.3941708	.15926	-2.47	0.013	-.706321	-.082021	.907514
headwork*	.0470207	.08493	0.55	0.580	-.119437	.213478	.398844
whobuilt*	.1322373	.11495	1.15	0.250	-.093058	.357532	.196532
terrain*	-.0976621	.0774	-1.26	0.207	-.249361	.054037	.526012

(*) dy/dx is for discrete change of dummy variable from 0 to 1

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