Cooperation, Games, and Ecological Feedback: Some Insights from Bali

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January 13, 2004

Abstract

For centuries Balinese rice farmers have been engaged in cooperative agricultural practices. Without centralized control, farmers have created a carefully coordinated system that allows productive farming in an ecosystem that is rife with water scarcity and the threat of disease and pests. We develop a simple game-theoretic model, inspired by a generation of careful anthropological field work, to provide a compact explanation for many of the most salient features observed in the system. We find that

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while externalities caused by either water scarcity or pests would, in isolation, be expected to cause a serious failure in the system, the ecology of the rice farming system links these two externalities in such a way that cooperation, rather than chaos, results. We test key features of the model through both natural and computational experiments and a field survey focused on the strategic motivations of the farmers.

Keywords: cooperation, game theory, irrigation, rice agriculture, Bali

1 Introduction

For centuries Balinese rice farmers have been engaged in cooperative agricultural practices (Wisseman, 1992; Scarborough *et al.*, 1999, 2000). This remarkable achievement in sustainable agriculture is surprising given the absence of any centralized control mechanisms and water supply conditions that would normally result in a rapid breakdown of cooperation due to severe externalities. An important cultural element of this system includes an elaborate hierarchy of decentralized water temples that helps to coordinate farming practices (Geertz, 1980; Lansing, 1991). Here, we develop a simple game-theoretic model that links together important features of both the human and ecological systems. The model provides an explanation for some of the key features that have been uncovered in this system, in particular, the emergence of cooperative farming practices in a decentralized system with severe externalities and the existence and legitimacy of the water temple system. We test the resulting model through both natural and computational experiments and a field survey focused on the strategic motivations of the farmers.

To foreshadow the results, we find that the typical breakdowns in cooperation one would expect to arise as upstream farmers ignore the water needs of downstream farmers are mitigated by the threat of crop pests. Given the ecology of the system, coordinated crop schedules—especially simultaneous fallow periods—can serve as a very effective pest control strategy. Thus, upstream farmers may have an incentive to cooperate by sharing water with downstream farmers so as to minimize pest damage. Depending on the ecological links among the various fields, coordinated planting may arise and create the need for an external coordination device—a role easily filled by the observed system of water temples. We conjecture that the specific patterns and control structure of the temples broadly correspond to the coordination needs dictated by the various ecological links inherent in the ecosystem. One unusual implication of the model is that, under some circumstances, increasing the level of pest damage in the ecosystem can actually *increase* aggregate agricultural output.

2 Background

In Bali, rice is grown in paddy fields fed by elaborate irrigation systems dependent on seasonal rivers and ground water flows. Gravity-fed irrigation works route the water to the various fields. The rugged topography and interconnections among the fields creates a highly interdependent system that can, at times, be quite fragile and subject to major disruptions.

Water performs a variety of complex biological processes in the rice paddy ecosystem. Careful control of the flow of water into the fields creates pulses in several important biochemical cycles necessary for growing rice. Water cycles have a direct influence on soil PH, temperature, nutrient circulation, aerobic conditions, microorganism growth, weed suppression, etc. In general, irrigation demands are highest at the start of a new planting cycle, since the dry fields must first be saturated with water.

The flooding and draining of blocks of terraces also has important effects on pests (including insects, rodents, and bacterial and viral diseases). The issue of pests is not a recent development—traditional Balinese lontar manuscripts, such as the *Dharma Pamaculan*, have references to *hama merana* (rice pests), and both Balinese and Dutch colonial sources refer to devastating plagues of rats in the paddy fields (Korn n.d.). If farmers with adjacent fields can synchronize their cropping patterns to create a uniform fallow period over a sufficiently large area, rice pests are temporarily deprived of their habitat and their populations can be sharply reduced. Field data indicate that synchronized harvests result in pest losses of around 1% compared to losses upwards of 50% during continual cropping. How large an area must be fallow, and for how long, depends on specific pest characteristics (Widiarta *et al.*, 1990; Aryawan *et al.*, 1993; Holt *et al.*, 1996; Latham, 1999).

Of course, if too many farmers follow an identical cropping pattern in an effort to control pests, then peak water demands will coincide. The existing watershed often does not have sufficient water to meet the full needs of all farmers in such a case.

Paralleling the physical system of terraces and irrigation works, the Balinese have constructed intricate networks of shrines and temples dedicated to agricultural deities and the Goddess of the Lake. These temples *de facto* provide farmers with a way to coordinate cropping patterns and the phases of agricultural labor. An example of a water temple system in the upper reaches of the Petanu river in southern Bali is shown in Figure 1. As the map indicates, the Bayad weir provides water for a hundred hectares of rice terraces organized as a single *subak* or farmer's association. A few kilometers downstream from the Bayad weir is the Manuaba weir, which provides water for 350 hectares of terraces, organized into ten subaks. The water temple hierarchy at Bayad consists of a weir-shrine (Pura Ulun Empelan) and a "Head of the Rice fields" temple (Pura Ulun Swi) situated above the terraces. The larger Manuaba system also begins with a weir-shrine, but includes two Pura Ulun Swi temples, one for each major block of terraces. The congregations of both Pura Ulun Swi temples also belong to a larger Masceti temple that is symbolically identified with the entire Manuaba irrigation system. Representatives of the ten subaks under the two Pura Ulun Swi temples meet once a year at the Masceti temple to decide on a cropping pattern. The degree of nested control apparent in the above description is typical of the overall temple system. The spatial pattern of agricultural temples varies from one watershed to another for both ecological and historical reasons.

3 A Model

To gain insight into the above system we propose a very simple game-theoretic model.[1] By design, we assume a trivial ecological structure and rely on some simple game-theoretic solution concepts; Nevertheless, the resulting model is surprisingly insightful. At the outset we recognize that a variety of extensions are available, though we feel that such additions will not fundamentally alter

[1] Ostrom (1996) relies on a model of similar spirit to consider collective issues that arise from upstream/downstream water externalities on Nepalese canals.

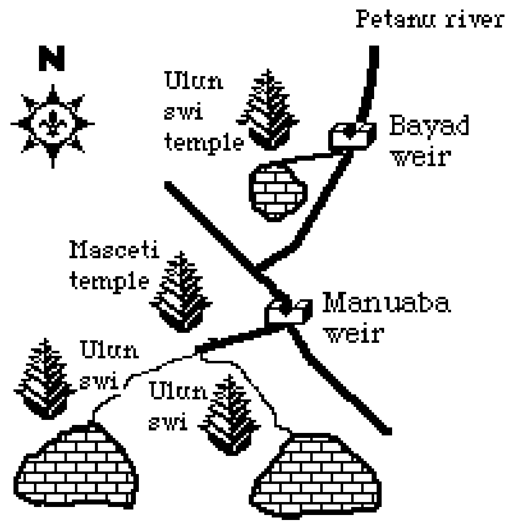

Figure 1: Petanu river water temple system.

our conclusions.

Suppose that there are only two rice farmers, one upstream from the other. We allow the upstream farmer to have first claim on any water in the system. To simplify matters, suppose that farmers must choose one of two possible dates on which to plant their crops, A or B. As in the Balinese ecosystem, we assume that the water supply is adequate to accommodate the needs of a single farmer during any given period, but it is insufficient if both decide to plant simultaneously. Let δ $(0 < \delta < 1)$ give the crop loss due to reduced water inputs experienced by the downstream farmer if he plants at the same time as the upstream farmer.

If the farmers do not plant simultaneously, we assume that both fields will

	A_d	B_d
A_u	$1, 1-\delta$	$1-\rho, 1-\rho$
B_u	$1-\rho, 1-\rho$	$1, 1-\delta$

Table 1: Payoffs for the game.

suffer damage due to pests being able to migrate back and forth during the growing cycles. Let ρ ($0 < \rho < 1$) give the crop loss due to pest migration between the fields under these conditions (we assume that there is no such damage if the crops are planted simultaneously). Given the above, the payoff matrix (numerated in crop output, with the payoff to harvesting an unencumbered field normalized to one) of the associated game is given in Table 1, where the rows (columns) represent the choices of the upstream (downstream) farmer (subscripted by u and d respectively).

The Nash (1950) equilibria of this game provide a variety of insights. The game always has a single, mixed-strategy Nash equilibrium where both players randomize with equal weight over the two starting times. The expected aggregate crop yield from the mixed strategy is $2 - \delta/2 - \rho$. Two pure strategy equilibria (either both planting at time A or both planting at time B) arise when $\delta \leq \rho$. Thus, when $\delta \leq \rho$, the game can take the form of a simple coordination game where the two players would like to plant at the same time. In either of the coordinated equilibria, the aggregate production is equal to $2 - \delta$. Note that the coordinated outcome will yield a greater aggregate harvest than the mixed strategy outcome when $\rho > \delta/2$. This holds since pest damage is borne by both farmers, while water damage only impacts the downstream farmer, thus aggregate yields increase by coordinating when pest damage is at least half as bad as water damage.

Figure 2 summarizes the above results. In this figure, parameter values below the 45° line can only support the mixed-strategy equilibrium, while those above this line can, in addition, support the two pure-strategy equilibria. In terms of aggregate crop output, either of the pure-strategy equilibria result in greater output than the mixed-strategy equilibrium for all parameters above the dashed line (that is, in the shaded area). In particular, note that for all parameter values in the region between the dashed and 45° lines, such as point a, aggregate output would be greater at either of the pure-strategy equilibria even though only the mixed strategy is supported. This leads to a rather counter-intuitive implication: for any such point we could potentially improve the aggregate crop output by increasing the damage done by pests (that is, by increasing the value of ρ). By increasing pest damage under such circumstances, we can move the system into a regime where coordination becomes a viable strategy, and since pest damage is fully mitigated under coordination, aggregate crop output increases.

Intuitively, the model's underlying logic is simple. There are two important externalities in the system: water damage (δ) imposed by the upstream farmer on the downstream farmer and pest damage (ρ) imposed by both farmers on each other by staggered cropping. The upstream farmer is not impacted by water scarcity, and thus always has an incentive to minimize pest damage by simultaneous cropping. The downstream farmer faces either water scarcity (under simultaneous cropping) or pest damage (under staggered cropping), and thus

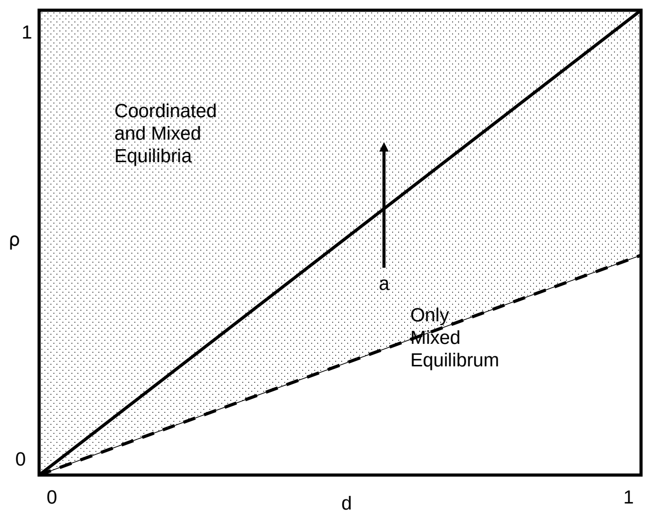

Figure 2: Game equilibria.

will choose the lesser of two evils. If pest losses are low, the downstream farmer wants to stagger cropping due to water considerations while the upstream farmer wants to plant simultaneously to avoid pest damage, and a mixed-strategy ensues. If, however, pest losses are high, both farmers' incentives are to coordinate on one of the two possible simultaneous cropping patterns.

Thus, if pests are bad enough (that is, if $\rho \geq \delta$), then a coordinated solution emerges with both farmers receiving higher individual crop yields than they would expect under the mixed-strategy outcome. Given that the two resulting pure-strategy equilibria of the coordination game yield identical outcomes, both of which are better than the mixed-strategy outcome, there is an important role for an external coordination device—like the water temple system—for determining which of the two equilibria to play. Note that such an entity does not require any formal enforcement power to remain credible, as it is in the individual interest of the farmers to follow whatever edict they collectively choose to impose upon themselves in the water temple (formally, this is known as a coordinated equilibria).

As discussed above, there is also a range of parameters under which the aggregate yield is likely to improve if *more* pest damage occurred. This paradoxical results occurs when $\delta > \rho > \delta/2$. In this range of ρ, either of the coordinated outcomes has higher aggregate crop yields than the mixed-strategy outcome, but only the mixed-strategy equilibrium is supported. Under such circumstances, if we increase ρ to ρ' (such that $\rho' > \delta$), the two pure-strategy equilibria become supported and aggregate output can be increased if one of them is adopted by the farmers.[2] When crops are staggered the aggregate yield falls due to pest damage to *both* fields as opposed to simultaneous cropping which has water damage to only one field. Nevertheless, the downstream farmer has no incentive to incorporate the pest damage to the upstream field in his decision calculus, and therefore it is possible for the downstream farmer to prefer staggered cropping even though this lowers aggregate yield. By increasing the pest damage, the downstream farmer will eventually prefer the water damage of simultaneously cropping to the pest damage of staggered cropping, thus eliminating the pest damage to both fields. Although the aggregate yield will increase, the down-

[2] Note that this result requires that the increased pest damage does not also impact the crops under simultaneous cropping. Empirically, it does appear that almost all pest damage is mitigated by simultaneous cropping.

stream farmer is worse off under the higher pest conditions, since the initial level of pest damage was such that this farmer would have preferred to incur pest damage rather than accept the water damage inherent in the coordinated outcome.

There is another potential path to improving aggregate crop output when the parameters are such that the downstream farmer would prefer not to coordinate. Recall from Figure 2 that parameters below the 45° line can only support the mixed-strategy equilibrium. However, there are circumstances in which the upstream farmer may be willing to pass on some of the water in order to induce the downstream farmer to cooperate. For example, suppose that the crop damage due to water, δ, can be shared between the two farmers[3] by the upstream farmer taking less than the full amount of water (and, in so doing, losing some crop) and passing it on so that the downstream farmer can experience lower crop losses. It can be shown that there is some damage sharing arrangement in which both farmers will be willing to coordinate cropping for any parameters in the range between the 45° and dashed lines in Figure 2. Moreover, as the parameters move from the 45° line toward the dashed line, the upstream farmer will be forced to provide a more equal distribution of the loss, that is, the water will need to be more evenly shared between the two farmers, to make the arrangement work.

Although the model above is intentionally simplified, it appears to be robust

[3] More formally, we assume that the damage can be divided linearly between the two farmers, with the upstream farmer experiencing $\alpha\delta$ and the downstream farmer receiving $(1-\alpha)\delta$ damage for $\alpha \in (0, 1)$.

to a variety of changes. For example, the introduction of higher yielding crops can be modeled by multiplying all of the payoffs by a constant—such transformations have no impact on the analysis.[4] Instead of simultaneous choices, we could allow one farmer to move first in the game. In the case where the farmers' incentives differ, the outcome of the game would depend on who moved first; If they both want to coordinate, then the first move could serve as a coordination mechanism.

In the model we also assumed that there were just two players: an upstream and downstream farmer. In Bali, typically each such "player" is in reality composed of many individual farmers who associate together as a single subak. Thus, our model assumes that each subak would act as a single entity. This assumption could be violated if, say, individual farmers within a given subak free ride on any group agreements, and thereby destroy the ability of a given subak to act as a unified entity. While more explicit models of subak decision making are of interest, there are some key factors in Bali which tend to enforce subak cohesion. In particular, given the proximity and low mobility of individual farmers within a given subak, individuals have very long-term interactions with one another across a variety of social and economic realms, ranging from agriculture to marriage, in an environment in which behavior is easily observed by others. In such a world, the long shadow of the future, multiple ties, and easily available information, tend to promote very high levels of cooperation. Indeed, survey evidence presented below suggest that farmers believe that key

[4] In reality, such crop varieties tend to be much more susceptible to pest damage, suggesting that ρ should be increased disproportionately.

economic outcomes are closely tied to those of fellow subak members. Moreover, subaks have elaborate codified rules that enforce cooperation within the group once a decision has been taken, by punishing those individuals who violate the rules with both informal and formal sanctions. Indeed, it is said that "the voice of the subak is the voice of God."

Finally, we could also incorporate more realistic ecological considerations into the theory, and below we employ a computational model of the system with such assumptions. Even in these more advanced models, the basic insights gleaned from the simple model above hold.

4 Further Evidence for the Model

The model developed above suggests a basis for the decentralized, self-organizing aspects of Balinese rice agriculture uncovered by Korn (1932), Geertz (1980), and Lansing (1991). It suggests that, even in the presence of a severe water externality, farmers should be willing to coordinate the simultaneous planting of crops to mitigate the potential of pest damage. Moreover, it points to the need for some type of institutional arrangement, like the water temples, to facilitate coordination. Such institutions need no formal enforcement power (such as the threat of force or ostracism), as each farmer has an incentive to seek, and follow, whatever advice is given.

Below we offer some additional support for the model. We show how a natural experiment, the mandated year-round cropping of high-yielding varieties of rice that destroyed the coordination in the system, resulted in an outbreak of pests, lowered aggregate output, and eventually a resumption of coordinated farming. Through the use of a computational model developed separately, we explore the consequences of extending the model to multiple players in a more ecologically realistic framework, and show how lowering the damage due to pests, can cause system-wide coordination to breakdown. Finally, we use a field survey to demonstrate that the strategic concerns of upstream farmers differ, in predictable ways, from those of the downstream farmers.

4.1 A Natural Experiment

The history of Bali offers an important natural experiment in the early 1970's. The development of new, high-yielding varieties of rice prompted the Balinese government, on the advice of consultants from the Asian Development Bank, to undertake a massive redirection of agricultural policy. By 1977, 70% of rice terraces in south-central Bali were planted with the new varieties of rice. To accomplish such a rapid change, the government legally mandated the double- and triple-cropping of these new varieties of rice. This led to the abandonment of the temple system of irrigation control, and therefore produced a situation where the previous coordination mechanism was rendered ineffective.

Soon after these mandated changes, district agricultural offices began to report "chaos in the water scheduling" and "explosions of pest populations" (1991). Attempts to mitigate the pest problem by introducing new crop varieties resistant to the existing pests resulted in the emergence of new pests—thus destruction of crops by the brown planthopper was reduced with the introduction of planthopper-resistant IR-36, but this variety was quickly overwhelmed by tungro virus, which was reduced by the introduction of PB 50, which unfortunately proved susceptible to *Helminthosporium oryzae*. The cropped areas experienced dramatic output declines between 1982 and 1985. Crop losses due to pests approached 100% in some areas, irrigation flows became chaotic, and so on. Balinese farmers remember the episode as the time of "poso" (hunger and harvest failures).

By the mid-1980's, the importance of the water temple system— previously noted in official reports only as a Balinese "rice cult"—was slowly recognized by government officials. The natural experiment of the breakdown of coordination during the Green Revolution provides support for the importance of coordination mechanisms in this system. The ecosystem is such that without careful coordination it experiences massive crop losses, and ultimately lower aggregate output, due to exploding pest populations. This resulted in strong pressure from the farmers to re-institute coordination mechanisms despite resistance from consultants and officials supporting the modernization program. The government now recognizes and supports the role of water temples in pest control (Lansing et al., 2001).

4.2 An Artificial Experiment

Another test of our theoretical ideas relies on the computational model of Lansing and Kremer (1993, 1998). This model captures major hydrological and biological features of 172 subaks relying on the Oos and Petanu rivers in the region of Gianyar. The model incorporates various water flows, pest damage and migration rates, and crop characteristics. Tests of the model across two harvests in 1989 suggest that the correlation between predicted and actual crop yields is around 0.90. The model was developed independently of the theory presented here and is driven by an adaptive model of bounded-rational agents.

The computational model attempts to capture the dynamical behavior, both ecologically and behaviorally, of all 172 subaks in the watershed (see Figure 3). In the model, the amount of water flowing at any point in the rivers and irrigation systems is determined by the seasonal patterns of rainfall and ground water flow, irrigation diversions, and crop use. An ecologically realistic model governs the growth of crops (either rice or vegetables) and the population dynamics of pests.

The behavior of each subak in the model follows a simple adaptive rule. At the end of each "year" of the simulation, every subak compares its harvest with that of its four closest neighbors. If any of the neighboring subaks have higher yields, then the target subak copies the cropping pattern of its (best) neighbor for the forthcoming year. The model continues in this manner until each subak reaches a local optimum.

Experiments with the above model indicate that the system quickly settles down to a stable pattern of cropping behavior. Over many hundreds of simulations, Lansing and Kremer found that the behavior of each subak stabilized within ten model years (assuming realistic parameter values). Moreover, these

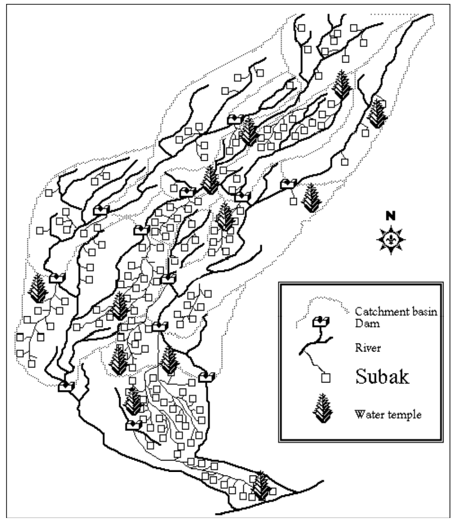

Figure 3: Watershed features in the computational model.

patterns coincided with the actual cropping patterns observed under the current water temple system. To test our theoretical ideas, we can manipulate the various parameters in the computational model, in particular, pest damage, and see if the resulting patterns of coordination and agricultural output are consistent with our predictions.

Figure 4 shows a graphical representation of the crop coordination implied by the computational model as a function of the virulence of pests. Each panel shows the ending state of a single trial of the model after ten years of simulated time.[5] Fields marked with the identical color follow the identical cropping/irrigation schedule. All three panels used identical parameters (normal

[5]Repeated runs of the model did not result in qualitatively different results.

Figure 4: Results from an artificial experiment using the model of Lansing and Kremer (1993). The outcomes reflect three levels of pest damage: low (left), current (middle), and high (right), and fields with the identical color coordinate their cropping.

rainfall and ground water flows, double cropping of Balinese cicih rice, and random crop timing in the initial year), except for the level of pest damage. Pest damage was either low (left panel), current (middle panel), or high (right panel), where current reflects parameters consistent with present-day ecological conditions. As is evident from the figure, under low pest damage we see very little coordination overall, with only some very local coordination on adjacent fields. As pest damage increases to parameters that reflect the current situation, we see large blocks of coordinated cropping emerging along the tributaries. Finally, as we increase pest damage even more, there is a a slight refinement in coordination, though most of the available gains have already been exploited.

The artificial experiment also predicts that as cooperation spreads, average rice harvests will increase throughout the watershed as pests and water are brought under effective control. However, such increases in harvests might contain the seeds for conflict. In particular, behavioral ecologists have suggested that envy, stemming from a disparity in benefits, may threaten cooperation among individuals. Thus if the results of cooperative arrangements are associated with a perceptible variation in the harvests we may find that feelings of envy among the farmers could hamper cooperative arrangements.

In the artificial experiment we find that as cooperation spreads, harvests tend to even out across the subaks. As cooperation emerges in the model, everyone obtains nearly identical yields, which average out to be better than any of the yields obtained prior to cooperation. The predictions of the experiment can be verified through some data collected in the field. In a survey of forty farmers in the Petanu watershed, we found that 97% of them believe that their own harvest is about the same as that of the other farmers in their subak.[6] Measurements of actual harvests, suggest that indeed yields across test plots are typically within 5% of one another.

4.3 Strategic Concerns

A final test of our model's formulation is to see whether or not the strategic concerns of the farmers in the system coincide with those in the model. Recall that given the nature of the two externalities, upstream farmers should focus

[6] These beliefs gain much more variance when farmers are queried about yields in other subaks—presumably an area in which their information is much less reliable.

their strategic considerations on pest damage while downstream farmers should be more concerned about water scarcity.

A field survey conducted in 1998 provides some useful data about the concerns of the farmers. The survey was conducted across ten separate subaks. In each subak, a stratified random sample of fifteen farmers was conducted, with five farmers each drawn from the upstream, middle, and downstream part of the subak. Each farmer was asked: "Which problem is worse, damage from pests or irrigation water shortages?"

The results of the survey, stratified by each farmer's relative location in their subak, are summarized in Figure 5. As can be seen from the figure, the upstream farmers within any given subak tend to be concerned about pests and water damage at roughly equal levels. However, farmers in the middle or downstream parts of the subaks are almost exclusively concerned about water shortages. Thus, even within a given subak, there appears to be strategic concerns that align well with the assumptions of the model. Note that we would typically expect intra-subak coordination and cooperation to be easier than inter-subak coordination, since within any given subak there are a variety of local mechanisms—including, better information about the actions of others, familial ties, and repeated interactions across other social and economic activities—that should promote cooperation. Such mechanisms are not typically available across subaks.

Given that there are within-subak mechanisms that should promote coordination, we would expect to see a stronger separation of concerns if we analyze

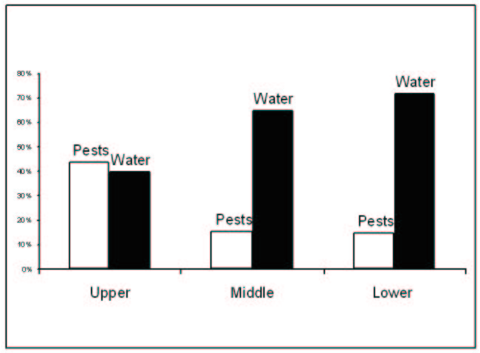

Figure 5: Survey responses by farmers about major concern, stratified by field location (relative to water supply) within a given subak. ($N = 150$.)

the data at the subak level. Of the ten subaks in the sample, six of them can be paired into direct upstream/downstream neighbors, where in each of these pairs, one of the subaks obtains most of its water from the other. In Figure 6 we summarize the results of the survey for the six-subak subsample aggregated by subak location. We find that, indeed, farmers in upstream subaks consider the threat of pests to be much more of a concern than water, while those in downstream subaks have the opposite focus. The above survey results nicely reflect the strategic concerns we would expect given the model.

Some additional support for the model comes from videotaped records of monthly inter-subak meetings. During these meetings, the heads of the ten subaks (plus four others not included in the sample) got together and discussed

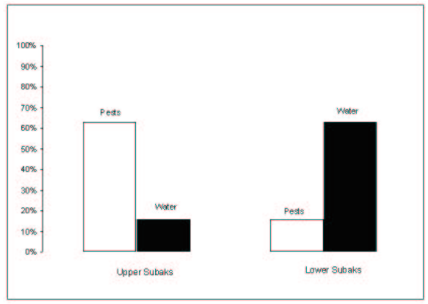

Figure 6: Survey responses by farmers stratified by subak location for a subsample of six, paired subaks. ($N = 90$.)

issues relevant to the group. We find that the perceived threat of pest invasion appears to be strongly related to the willingness of the heads of upstream subaks to synchronize cropping. Indeed, environmental conditions seem to play a major role in the negotiations. In years of high pest damage, more synchronization is observed, while in years of light rains, greater fragmentation ensues (Lansing, forthcoming). Again, such observations are consistent with the predictions of the model.

5 Conclusions

The cooperation that sustains the Balinese rice farming system is truly remarkable. Without centralized control, farmers have created a coordinated system that allows productive farming in an ecosystem that is rife with water scarcity and the threat of disease and pests. The game-theoretic model we develop above, inspired by a generation of extensive anthropological field work, provides a compact explanation for many of the most salient features we observe in the system.

While externalities caused by either water scarcity or pests would, in isolation, be expected to imply a serious failure, the ecology of the rice farming system links these two externalities in such a way that cooperation, rather than catastrophe, is the result. Depending on the underlying ecological parameters in the system, there are regimes in which the farmers would like to carefully coordinate their cropping patterns (in particular have identical fallow periods) so as to control pest populations. There are other regimes in which coordination is not an equilibrium, even though coordinated farming would result in greater aggregate crop output. We identify at least two indirect mechanisms by which the system can escape from such a trap. The first is to have the upstream farmers share their water with the downstream farmers, and we find that under many circumstances, both parties are willing to engage in such bargains. The second, a bit more counterintuitive, is that increases in pest damage can drive the system into a coordinated equilibrium enhancing aggregate output.

Whenever the system is such that the farmers want to coordinate their activities, there is a need for some mechanism to facilitate the coordination. We suggest that the observed system of Balinese water temples fills such a role (of course, the temples have many other functions as well). Even without any direct enforcement power, the value of a centralized coordination device would give such an institution legitimacy.

The Balinese rice farming system provides a nice opportunity to combine intensive field anthropology with formal modeling, to the benefit of both. It is rare to have such rich ecological and social data from which to inform, and test, game-theoretic ideas. Moreover, the modeling suggests a number of insights that may help explain some of the details uncovered by the field work. While we do not wish to deny the role of more complex cultural factors in promoting cooperation, we suspect that the challenge is to place such factors in the context of the ecological tradeoffs highlighted by the model.

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Figure 3: Results from an artificial experiment using the model of Lansing and Kremer (1993). The outcomes reflect three levels of pest damage: low (left), current (middle), and high (right), and fields with the identical color coordinate their cropping.