Reports

Cooperation, Games, and Ecological Feedback: Some Insights from Bali[1]

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For centuries Balinese rice farmers have been engaged in cooperative agricultural practices (Christie 1992; Scarborough, Schoenfelder, and Lansing 1999, 2000). This remarkable achievement in sustainable agriculture is surprising given water supply conditions that would normally result in a rapid breakdown of cooperation and the absence of any centralized control mechanisms. An important cultural element of this system includes networks of water temples that help to coordinate farming practices (Geertz 1980, Lansing 1991). Here we develop and test a simple game-theoretic model that links important features of the human and ecological systems and provides an explanation for the emergence of cooperative farming practices in a decentralized system with severe externalities and the coordinating role of the water temple system.

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. Simultaneous fallow periods can serve as an 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.

BACKGROUND

In Bali, rice is grown in paddy fields fed by elaborate irrigation systems dependent on seasonal rivers and groundwater flows. Gravity-fed irrigation works route the water to the distant fields, creating a highly interdependent system that is physically fragile.

In general, irrigation demands are highest at the start of a new planting cycle because the dry fields must first be saturated with water. The flooding and draining of blocks of terraces 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 with 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 and Chancellor 1996, Latham 1999). Of course, if too many farmers follow identical cropping patterns in an effort to control pests, then peak water demands will coincide. Often there is insufficient 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 (Lansing 1991).

A MODEL

To gain insight into the above system we propose a very simple game-theoretic model.[2] By design, we assume a

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[2] Ostrom (1996) relies on a model of similar spirit to consider

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, but we conjecture that such additions will not fundamentally alter 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*. We assume that the water supply is adequate to accommodate the needs of one farmer during any given period but insufficient if both decide to plant simultaneously. Let $\delta(0 < \delta < 1)$ 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 suffer damage due to pests' being able to migrate back and forth during the growing cycles. Let $\rho(0 < \rho < 1)$ 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.

The Nash (1950) equilibria of this game provide a variety of insights. The game always has a single, mixed-strategy Nash equilibrium at which the two 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 in which the two players would like to plant at the same time. In either of the coordinated equilibria, the aggregate production is equal to $2-\delta$. The coordinated outcome will yield a greater aggregate harvest than the mixed-strategy outcome when $\rho > \delta/2$. This holds because pest damage is borne by both farmers while water damage impacts only the downstream farmer; thus aggregate yields increase by coordinating when pest damage is at least half as bad as water damage.

Figure 1. summarizes these results. Parameter values below the 45° line can support only 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 results in greater output than the mixed-strategy equilibrium for all parameters above the dashed line (that is, in the shaded area). In particular, 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 in which coordination becomes a viable strategy, and since pest damage is fully mitigated under coordination, aggregate crop output increases.

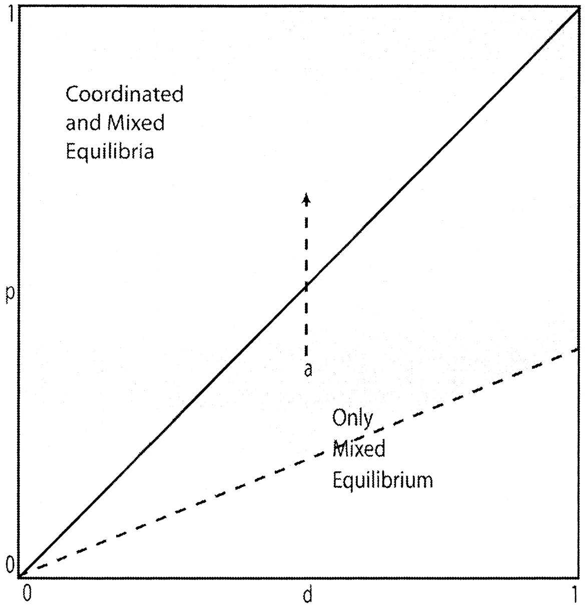

FIG. 1. *Game equilibria.*

Intuitively, the model's 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 therefore 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 therefore will choose the lesser of two evils. If pest losses are low, the downstream farmer wants to stagger cropping because of 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 have an incentive to coordinate on one of the two possible simultaneous cropping patterns.

TABLE 1
Payoffs for the Game

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

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collective issues that arise from upstream/downstream water externalities on Nepalese canals.

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 yield identical outcomes, both of which are better than the mixed-strategy outcome, there is an important role for an external coordination device—such as the water temple system—for determining which of the two equilibria to play. 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 equilibrium).

As we have said, there is also a range of parameters under which the aggregate yield is likely to improve if *more* pest damage 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 are supported and aggregate output can be increased if one of them is adopted.[3] When crops are staggered the aggregate yield falls because of pest damage to *both* fields. Nevertheless, the downstream farmer has no incentive to incorporate the pest damage to the upstream field in his decision calculus and may therefore prefer staggered cropping even though this lowers aggregate yield. As pest damage increases, the downstream farmer will eventually prefer the water damage of simultaneous cropping to the pest damage of stragged cropping, thus eliminating the pest damage to both fields. Although the aggregate yield will increase, the downstream 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 to 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. Suppose that the crop damage due to water (δ) can be shared between the two farmers[4] if, the upstream farmer takes less than the full amount of water (and, in so doing, loses some crop) and passes 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 the dashed line in figure 1. 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 this model is intentionally simplified, it appears to be robust 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.[5] Instead of simultaneous choices, we could allow one farmer to move first in the game. In the case in which the farmers' incentives differed, the outcome of the game would depend on who moved first; if they both wanted 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 a group of farmers known as a *subak*. Thus, our model assumes that each *subak* will act as a single entity. This assumption could be violated if, say, free-riding by individual farmers destroyed its ability 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 their proximity and low mobility, individuals within a *subak* have very long-term interactions with one another 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, 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.

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, such as the water temples, to facilitate coordination. Such institutions need no formal enforcement power (such as the threat of force or ostracism) because 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 reducing the damage due to pests can cause systemwide coordination to break down. Finally, we use a field survey to demonstrate that the strategic concerns of upstream farmers differ in predictable ways from those of downstream farmers.

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[3] This result requires that increased pest damage not also impact the crops under simultaneous cropping. Empirically it appears that almost all pest damage is mitigated by simultaneous cropping.

[4] 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 $\alpha\varepsilon(0,1)$.

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

A natural experiment. The history of Bali offers an important natural experiment. The development in the early 1970s of new, high-yielding varieties of rice prompted the Indonesian government 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, and the government mandated continuous cropping. This led to the abandonment of the temple system of irrigation control and thus rendered the previous coordination mechanism ineffective. Soon district agricultural offices began to report chaos in water scheduling and explosions of pest populations (Lansing 1991). By the mid-1980s the importance of the water temple system—previously noted in official reports only as a Balinese "rice cult"—was recognized by government officials (Lansing et al. 2001). The harvest losses caused by this breakdown of coordination provide further support for the importance of coordination mechanisms.

An artificial experiment. Another test of our theoretical ideas relies on the ecological model of Lansing and Kremer (1993; Lansing, Kremer, and Smuts 1998). This model captures major hydrological and biological features of 172 *subaks* relying on the Oos and Petanu Rivers in the region of Gianyar (fig. 2). The amount of water flowing at any point in the rivers and irrigation systems is determined by the seasonal patterns of rainfall and groundwater 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 correlation between predicted and observed crop yields for 1989 was 0.90.

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 most *subaks* reach 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, the behavior of each *subak* stabilized within ten model years (assuming realistic parameter values). Moreover, these patterns closely resembled the actual cropping patterns observed under the current water temple system. To test our theoretical ideas, we can manipulate the pest parameter and see if the resulting patterns of coordination and agricultural output are consistent with our predictions.

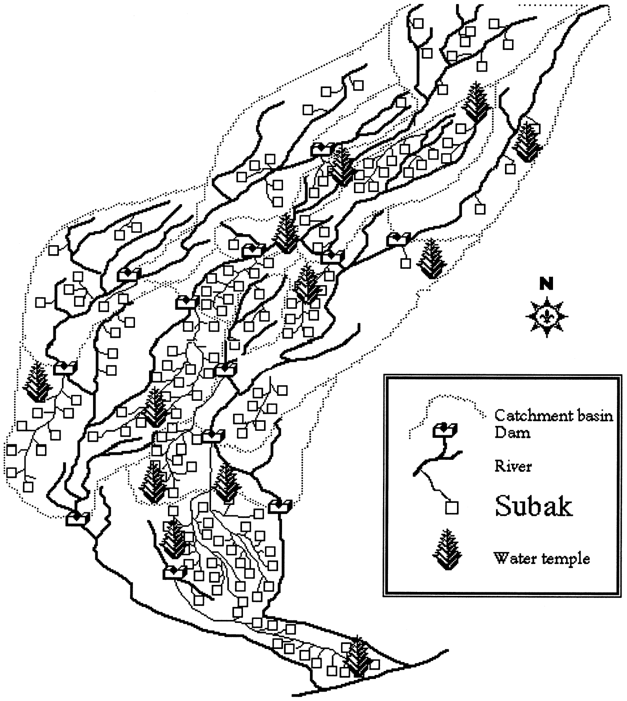

FIG. 2. *Watershed features in the computational model.*

Figure 3. represents the crop coordination implied by the ecological 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.[6] All three panels used identical parameters except for the level of pest damage (normal rainfall and groundwater flows, double cropping of Balinese *cicih* rice, and random crop timing in the initial year). Pest virulence was either low, current, or high, where "current" reflects parameters consistent with present-day ecological conditions. Under low pest damage we see negligible coordination. As pest damage increases to parameters that reflect the current situation, we see large blocks of coordinated cropping emerging along the tributaries. Finally, as pest damage increases even more, there is a a slight refinement in coordination, though most of the available gains have already been exploited.

This 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. Such increases in harvests may, however, contain the seeds for conflict. In particular, behavioral ecologists have suggested that envy stemming from a disparity in benefits may threaten cooperation. Thus if the results of cooperative arrangements are associated with a perceptible variation in the harvests envy may hamper cooperative arrangements. However, we find that as cooperation spreads, *subaks* obtain nearly identical yields which are better than any of the yields obtained prior to cooperation. These results were explored in a survey of 40 farmers in the Petanu watershed, in which 97% agreed that their own harvests were about the same as those of the other farmers in their *subak*.[7]

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

Strategic concerns. A final test is to see whether the strategic concerns of the farmers in the system coincide with those in the model. Given the nature of the two externalities, upstream farmers should focus their strategic considerations on pest damage while downstream farmers should be more concerned about water scarcity. A field survey conducted in 1998 in ten *subaks* provides some useful data about the concerns of the farmers. In each *subak*, a stratified random sample of 15 farmers was selected, with 5 farmers each drawn from the upstream, middle, and downstream parts 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 farmers' relative locations in their *subak*, are summarized in figure 4. The upstream farmers in 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 there appear to be strategic concerns within *subaks* that align well with the assumptions of the model. Given that there are within-*subak* mechanisms that should promote coordination, we would expect to see a stronger separation of concerns if we analyzed the data at the *subak* level. Of the ten *subaks* in the sample, six can be paired into direct upstream/downstream neighbors, in each pair of which one obtains most of its water from the other. In figure 5 we summarize the results of the survey of this subsample aggregated by *subak* location, which reflect the expected strategic concerns.

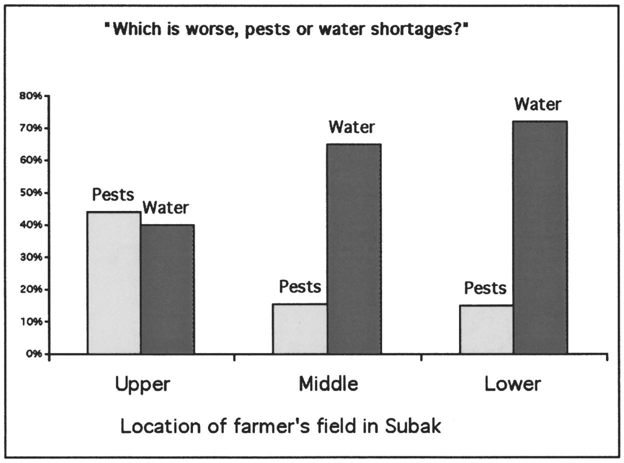

FIG. 4. *Survey responses about major concerns of farmers stratified by field location (relative to water supply) within a given* subak *(N = 150).*

Some additional support for the model comes from videotaped records of monthly intersubak meetings. 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. In years of high pest damage, more synchronization is observed, while in years of light rains, greater fragmentation en-

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[7] These beliefs acquired much more variance when farmers were queried about yields in other *subaks*—presumably an area in which their information was much less reliable.

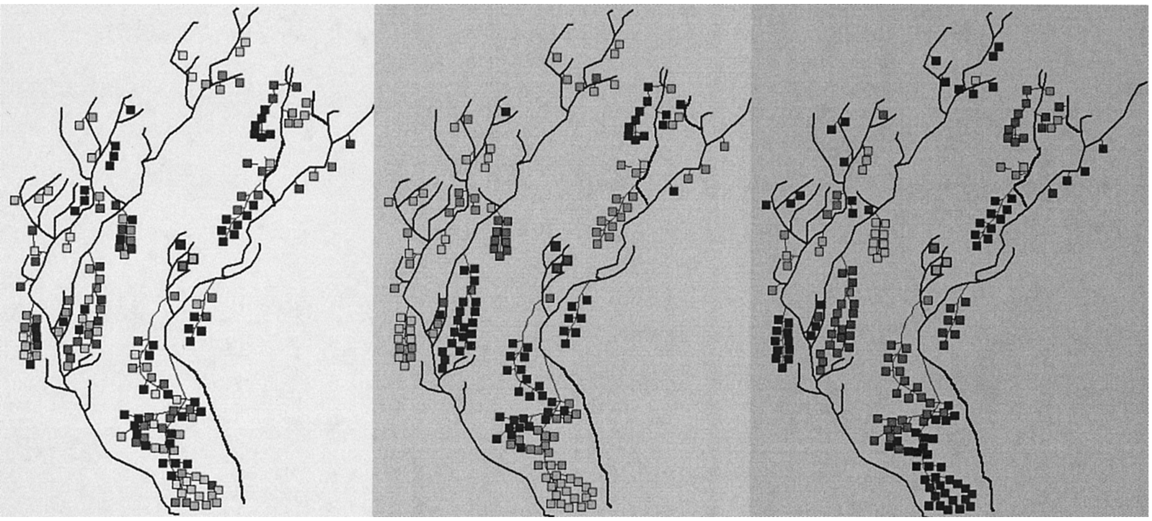

FIG. 3. *Results of an artificial experiment using the model of Lansing and Kremer (1993). Outcomes reflect three levels of pest damage: low (*left*), current (*center*), and high (*right*), and fields (*squares*) of the same shade follow identical cropping/irrigation schedules.*

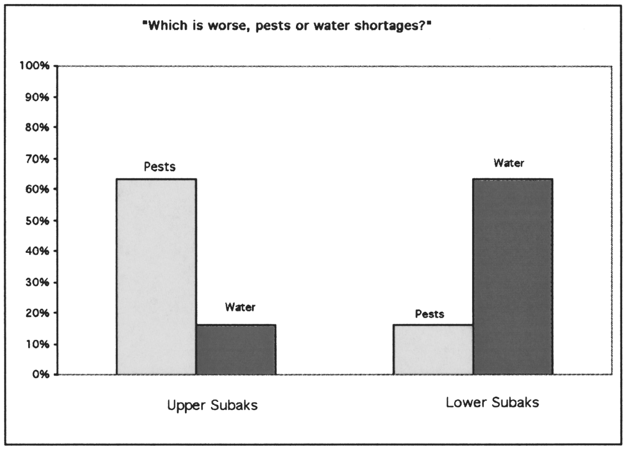

FIG. 5. *Survey responses about major concerns of farmers stratified by* subak *location for a subsample of six paired* subaks *(N = 90).*

sues, consistent with the predictions of the model (Lansing n.d.).

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 have developed provides a compact explanation for many of the most salient features of 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 can emerge. Depending on the underlying ecological parameters in the system, there are regimes in which the farmers would like to 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 for upstream farmers to share their water with downstream farmers, and we find that under many circumstances both parties are willing to engage in such bargains. The second is for increases in pest damage to 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 an opportunity to combine anthropology with formal modeling to the benefit of both. It is rare to have such rich ecological and social data with 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 fieldwork. 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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