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Emergent Properties of Balinese Water Temple Networks: Coadaptation on a Rugged Fitness Landscape

For over a thousand years, generations of Balinese farmers have gradually transformed the landscape of their island, clearing forests, digging irrigation canals, and terracing hillsides to enable themselves and their descendants to grow irrigated rice. Paralleling the physical system of terraces and irrigation works, the Balinese have also constructed intricate networks of shrines and temples dedicated to agricultural deities. Ecological modeling shows that water temple networks can have macroscopic effects on the topography of the adaptive landscape, and may be representative of a class of complex adaptive systems that have evolved to manage agroecosystems.

IN 1984, ERIC ALDEN SMITH PUBLISHED a devastating critique of the uses of systems ecology and simulation modeling in anthropology. While this article is in part a defense of these methods, we do not take issue with any of Smith's conclusions. Instead, we hope to demonstrate that systems models can serve a different heuristic purpose than the naive functionalist, energy-maximization or group-selection models skillfully demolished by Smith. In particular, we hope to show that simulation models are uniquely appropriate for addressing the issues of adaptation and determinism in the development of complex social systems like the water temples of Bali. But before we turn to the uses of simulation models, it may be useful to sketch out how our approach differs from those criticized by Smith.

Although simulation models have always been a rarity in anthropology, they continue to be used extensively in biology as a tool to investigate complex interactive processes. For example, we recently served on the doctoral committee of a graduate student who was interested in the growth of algae in Antarctic sea ice, a major source of fixed carbon in the Antarctic Ocean. The student built a model to study the interactive effects of processes thought to influence the growth of the algae, such as temperature, nutrient flow, and available sunlight. The result was a system of differential equations that predicted, on purely theoretical grounds, variations in the growth of algae depending on the relationships among these causal factors. The model's predictions were then compared with observations, helping the student fine-tune his understanding of the mechanistic processes that drive the growth of the algae (Arrigo 1991).

However, an obvious problem in extending this kind of analysis from biology to anthropology is that natural ecosystems evolve through a process of "blind" natural selection, while the systems of most interest to anthropologists are by definition shaped by conscious human intentions. Life in the sea ice of Antarctica is thought to have evolved opportunistically through the random effects of natural selection. On the other hand, centuries-old Balinese rice terraces would cease to function in a matter of days if Balinese farmers stopped managing them. It is precisely the introduction of human agency into natural ecologies that blunts the tools designed for the study of mindless processes.

Marx drew a distinction between two models of "nature" that is relevant to the point we are trying to make. On the one hand, according to Marx, there is "external nature," or nature apart from society: remote islands, or distant galaxies. Of greater interest to the social theorist is "humanized nature": those portions of the natural world that have been shaped by human intention (Habermas 1971:34). Significantly, this distinction does not depend on the presence or absence of people in an ecosystem, but rather on whether the natural system in question has been purposefully modified by human activities. For example, one of the unexpected results of the model of Antarctic sea ice was the realization that human society may soon have a significant negative impact on the Antarctic food chain. The reason is that global warming may shorten the growing season for algae by several weeks. From a methodological standpoint, there is no difficulty in modeling this effect in a computer simulation: it can be expressed in terms of a seasonal change in the rate of light absorption. But a new and different set of questions emerges when we turn from an ecosystem that has evolved through natural selection to one that has also been deliberately modified to suit human purposes. The question of purpose is meaningless in the context of the growth of algae in Antarctic sea ice, but essential to understanding the growth of rice in an irrigated terrace. In the latter case we are confronted with Hegel's "active practical reality of consciousness" shaping a natural landscape over the course of many generations.

"It is as clear as noon-day," Marx wrote in 1844, "that man, by his industry, changes the forms of the materials furnished to him by Nature, in such a way as to make them useful to him" (Marx 1961[1844]:71). So much may be obvious, but Marx added an important corollary: in the process of reshaping nature, society gradually reshapes itself. Anthony Giddens neatly summarizes this point: "Marx emphasizes that social development must be examined in terms of an active interplay between human beings and their material environment" (Giddens 1981:59). A similar insight led Fernand Braudel to formulate the concept of the "structures of the *longue durée*," although unlike Marx, Braudel emphasized the passivity of human societies held nearly immobilized by their environments:

For centuries, man has been a prisoner of climate, of vegetation, of the animal population, of a particular agriculture, of a whole slowly established balance from which he cannot escape without the risk of everything's being upset. . . . There is the same element of permanence or survival in the vast domain of cultural affairs. [Braudel 1980(1969):31]

Yet despite their differing perspectives on the active relationship of societies to the natural world, on a deeper level both Marx and Braudel agree that the intentionality of individual social actors, or even whole generations, is insufficient to explain the historical evolution of modes of production. Instead, both posit a historical evolution of consciousness as societies gradually reshape the natural world. Humanized nature is actively transformed by social action, and gradually acquires a purposive structure, which sharply distinguishes it from the universe of "external nature." This distinction is particularly relevant when we address the question of change. If we could rewind an imaginary videotape of the evolution of life, as Stephen Jay Gould observes in *Wonderful Life: The Burgess Shales and the Nature of History*, each sequence would show us not design not contingency. The paleontologist cannot predict which species will thrive, and which become extinct, because the process of change is always local, contingent, and unpredictable:

The divine tape player holds a million scenarios, each perfectly sensible. Little quirks at the outset, occurring for no particular reason, unleash cascades of consequences that make a particular future seem inevitable in retrospect. But the slightest early nudge contacts a different groove, and history veers into another plausible channel, diverging continually from its original pathway. [Gould 1990:320-321]

But consider a tape showing the historical evolution of irrigation systems, rice terraces, and water temples in Bali over the past millennium. We would witness the engineering of the landscape, as generations of Balinese farmers cleared forests, dug irrigation canals,

and terraced hillsides to enable themselves and their descendants to grow irrigated rice. We might also see false starts, abandoned irrigation works, and conflicts between groups of farmers. But over time, the historical record would show us precisely what is missing from Gould's *prehistoric* record: the traces of conscious design. We would see the results of a stochastic process in which the realization of each generation's plans changed the world for their descendants.

In this article we try to show how the techniques of ecological simulation modeling can help to illuminate this historical process. The major difference between the modeling process that we describe, and the sorts of models used by biologists, is that here our interest focuses on the effects of human agency in reshaping ecosystems. History only happened once, of course, but with simulation models we can "rewind the tapes" and investigate the consequences of changing social and ecological parameters. This approach can help avoid one of the most common pitfalls in materialist approaches to social theory: the assumption that whatever social institutions happen to exist at a particular place and time are the deterministic results of environmental circumstances. For while the evolution of productive systems like irrigation networks is undoubtedly shaped by material constraints, it does not follow that such constraints mandate a specific set of cultural and ecological responses.

The need for an approach that will enable us to analyze the effects of interactions between social and ecological variables over time is the reason for our disagreement with Eric Smith. Smith objects to simulation models on the grounds that they appear to be teleological, depicting ecosystems as self-regulating or functionally integrated (1984:66–70). In preference to systems ecology, which tries to study whole ecosystems, Smith urges us to adopt the perspective of evolutionary ecology, which focuses on calculations of the "fitness value" or payoff of specific behavioral strategies to individual social actors. But successful applications of evolutionary ecology in anthropology have been confined to studies of hunting-and-gathering societies, where arguably we are concerned with "external" rather than "humanized" nature. In this article, our major goal is to comprehend the emergence of cooperative behavior among Balinese farmers. Here, the "fitness value" or payoff of different farming strategies changes as a result of complex interactions between irrigation networks and the domesticated ecology of the rice terraces. To foreshadow the most interesting results, a spontaneous process of self-organization occurred when we allowed water temples to react to changing environmental conditions over time in a simulation model. Artificial cooperative networks appeared that bore a very close resemblance to actual temple networks in the study area. As these networks formed, average harvest yields rose to a new plateau. Subsequently, irrigation systems organized into artificial temple networks were able to withstand ecological perturbations (such as pest outbreaks or drought) much better than in otherwise identical models that lacked temple networks. It appears, then, that networks of water temples may have a definite structure, which leads to higher sustained productivity than would be the case if they were randomly ordered. Further, these structures can emerge without conscious planning, through a stochastic process of coadaptation. Thus water temple networks may represent a hitherto unnoticed type of social organization: a self-organizing managerial system, shaped by a process of coadaptation on a *rugged fitness landscape* (Palmer 1991; Kauffman and Johnsen 1991).

We begin with a brief analysis of the ecological role of water temples and a description of a simulation model we developed to explore the ecological role of water temples along two rivers. Tests of the model's predictions against two years of historical data added empirical support to the theoretical argument in *Priests and Programmers* (Lansing 1991:117–126) that water temples optimize rice harvests. In the second half of the article, we turn to the question of how the water temple networks manage to find optimal or near-optimal scales of coordination in water management. The entire ecological simulation model described in the first part of the article becomes a single time-step in a nonlinear model designed to explore the relative importance of trial and error versus conscious de-

sign in the evolution of temple networks. Finally, we return to the methodological issues raised by Smith.

The Ecological Role of Water Temples

In Bali, rice is grown in paddy fields fed by irrigation systems dependent on rainfall (there are no storage dams in the rivers). Rainfall varies by season and elevation and, in combination with groundwater inflow, determines river flow. Traditional Balinese irrigation systems begin with a weir in a river, which shunts all or part of the flow into a tunnel that emerges some distance downstream, at a lower elevation, where the water is routed through a system of canals and aqueducts to the summit of a terraced hillside. Thus, the flow of water into each farmer's fields depends on the seasonal flow of water in the rivers and streams, which in turn depends on rainfall and groundwater flow.

The role of water in the rice paddy ecosystem goes far beyond providing water to the roots of the rice plants. By controlling the flow of water into the terraced fields, farmers are able to create pulses in several important biogeochemical cycles. The cycle of wet and dry phases alters soil pH, induces a cycle of aerobic and anaerobic conditions in the soil that determines the activity of microorganisms, circulates mineral nutrients, fosters the growth of nitrogen-fixing cyanobacteria, excludes weeds, stabilizes soil temperature, and over the long term governs the formation of a plough pan that prevents nutrients from being leached into the subsoil. On a larger scale, the flooding and draining of blocks of terraces also has important effects on pest populations. 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 pest populations can be sharply reduced. How large an area must be fallow, and for how long, depends on the species characteristics of the rice pests. However, if too many farmers follow an identical cropping pattern in an effort to control pests, they will experience peak irrigation demand at the same time, and there might not be enough water for all, especially because the distance between weirs on Balinese rivers is usually only a few kilometers. Water sharing and pest control are thus opposing constraints, and the optimal scale for the coordination of cropping patterns depends on local conditions.

Paralleling the physical system of terraces and irrigation works, the Balinese have also constructed intricate networks of shrines and temples dedicated to agricultural deities and the Goddess of Waters. These temples play an instrumental role in the productive process by providing farmers with a structure to coordinate cropping patterns and the phases of agricultural labor. An analysis of the "ritual technology" that makes this possible is beyond the scope of this article (see Lansing 1987, 1991), but the ecological effects of temple networks can be clearly seen in the relationship between neighboring irrigation systems in the upper reaches of the Petanu River in southern Bali (Figure 1).

As the map indicates, the Bayad weir provides water for 100 hectares of rice terraces organized as a single *subak*, or farmer's association. A few kilometers downstream from the Bayad weir, the Manuaba weir provides water for 350 hectares or terraces, organized into ten subaks. The water temple hierarchy at Bayad consists of a weir-altar (*pura ulun empelan*) and a "Head of the Ricefields" temple (*pura ulun swi*) situated above the terraces. The larger Manuaba system also begins with a weir-altar, but includes two Ulun Swi temples, one for each major block of terraces. The congregations of both Ulun Swi temples also belong to a larger Masceti temple that is symbolically identified with the entire Manuaba irrigation system. Representatives of all ten subaks meet once a year at the Masceti temple to decide on a cropping pattern. Subsequently, the ritual calendar carried out at the Ulun Swi temples provides a template for the phases of agricultural labor.

For example, all ten subaks belonging to the Masceti temple planted IR 64, a high-yielding Green Revolution rice, in mid-September 1988 and harvested an average of 6.5 tons per hectare in mid-December. Subsequently, they planted kruing (another high-yielding rice) in early February and harvested 6 tons/ha in May. In June, they all planted

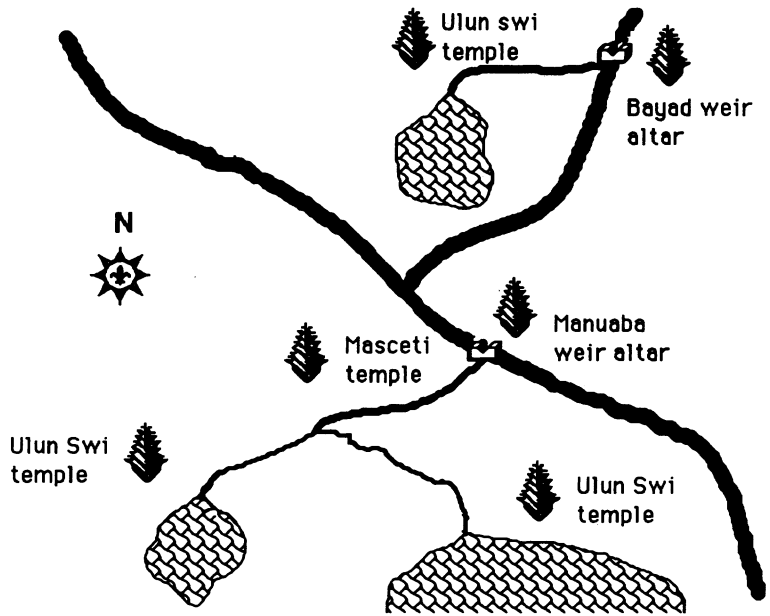


Figure 1
Bayad and Manuaba irrigation systems (from Lansing 1991:60).

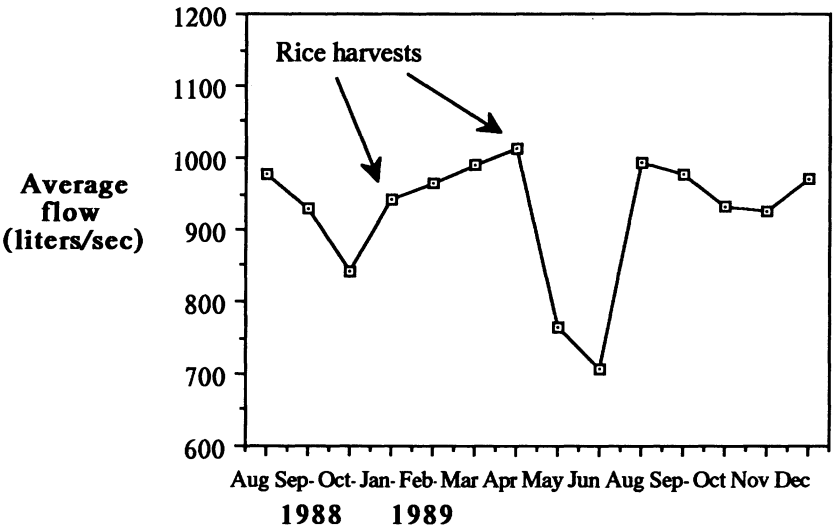


Figure 2
Flow at the Manuaba weir (1988–89).

vegetables and harvested approximately 2 tons/ha in August. During this time period, the flow of irrigation water into the Manuaba weir was as shown in Figure 2. This cropping pattern synchronized harvests for all ten subaks, encompassing 350 hectares of rice terraces, thereby possibly helping to keep down pest populations. Pest infestations for this period were reported to be minimal: less than 1% damage to the crops, primarily from brown planthoppers. This compares to pest losses of up to 50% of the crop in the late

1970s, when each subak planted rice continuously and cropping patterns were very disorganized (Lansing 1991:112–117). However, the average flow of approximately 3 liters per second per hectare is less than the recommended average flow of 5 liters/sec/ha, and suggests that the crops may have experienced some water stress. Certainly there was never any excess water. In that light, it is interesting to note that the Bayad subak upstream followed exactly the same cropping pattern as Manuaba, except that they began two weeks earlier. In general, irrigation demand is highest at the beginning of a new planting cycle, because the dry fields must become saturated. By starting two weeks after their upstream neighbors, the Manuaba subaks could help avoid water shortages at the time when irrigation demand peaks.

There would thus appear to be good ecological reasons for the Manuaba subaks to coordinate their cropping patterns with their upstream neighbors. The Bayad subak might also find that it is in their interest to coordinate their fallow periods with Manuaba, so as to keep down pest populations. As it happens, the Manuaba subaks regularly send a delegation to the Bayad weir to request holy water, and the interdependency of the two irrigation systems is given symbolic expression by ritual ties between the deities of the two weirs.

A Simulation Model of Two Rivers

In the case we have just considered, the water temples play their part by helping the subaks to balance two opposing constraints: water sharing and pest control. The effect of these constraints varies by location. In 1988, we built a simulation model to explore the effects of synchronized cropping patterns along two entire rivers, the Oos and the Petanu (Kremer and Lansing 1992a, 1992b). The model allowed us to simulate the effects of coordination by water temples under varying ecological conditions, and also to simulate other possible levels of coordination. At one extreme, all subaks follow exactly the same cropping pattern; at the other, each subak sets its own unique cropping pattern. The actual water temple scale of coordination lies between these extremes.

The watershed of the Oos and Petanu rivers includes approximately 6,136 hectares of irrigated rice terraces (Figure 3). Based on topographical maps, we divided the Oos-Petanu watershed into 12 subsections, specifying the catchment basins for each weir for which hydrological data was available. For each of the 172 subaks located in these basins, we specified the name, the area, the basin in which it resides, the weir from which it receives irrigation water, and the weir to which any excess is returned. We also defined the real spatial mosaic connecting these subaks. Given this geographical setting, the program simulates the rainfall, river flow, irrigation demand, rice growth stage, and pest levels for all watersheds and all subaks. At the appropriate times, the harvest is adjusted for cumulative water stress and pest damage, yields are tallied, and the next crop cycle is initiated (Kremer 1991).

In order to test the predictions of this model, in 1989 Lansing began to work with a team of Balinese students to gather real data on rainfall, irrigation flow, crop yields, water stress, and pest damage. As Figure 4 shows, there was a great deal of variation in actual harvest yields reported by the subaks (a point we return to later on). Subsequently, we loaded the model with rainfall records based on real monthly averages, assigned each subak a cropping pattern that approximated its real cropping pattern, and compared the results with the actual distribution of yields (see Figure 5). Considering the simplicity of the model, yields per hectare were also well correlated, with $r = 0.5$. To assess the possibility that model results were simply not very responsive to variations in cropping plans, we ran additional simulations in which we disrupted the local coordination implicit in the planting schedules followed by the subaks in 1989. When planting dates were randomized, but the actual crops planted remained the same, the correlation for the second crop in 1989 dropped from 0.50 to 0.01 (Kremer and Lansing 1992b).

Comparison of the effects of different scales of coordination by the subaks for many simulation runs showed that the scale of coordination that most closely resembles the

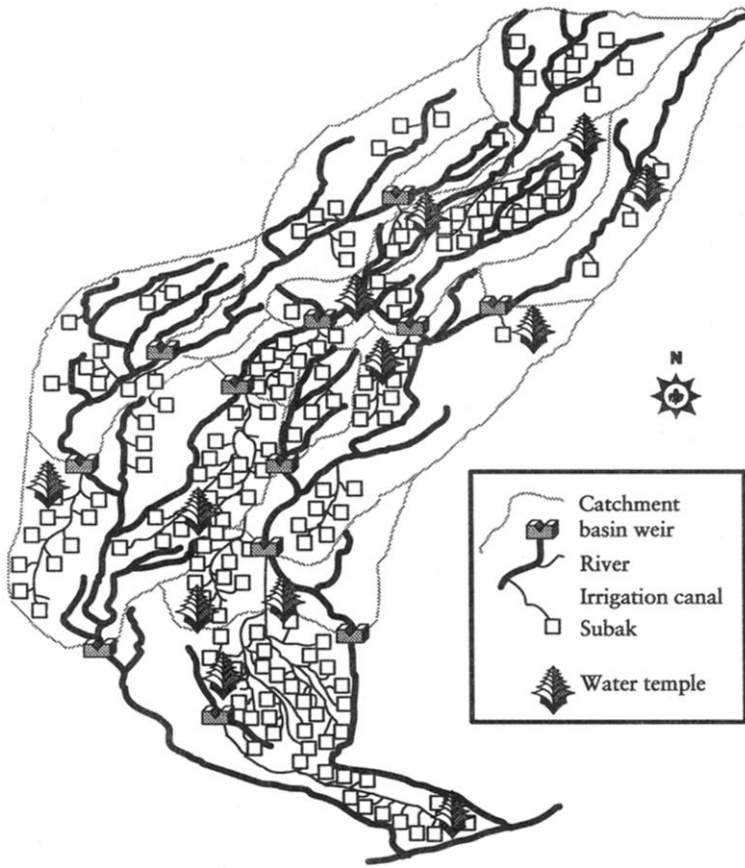


Figure 3

The Oos and Petanu rivers in south-central Bali (not to scale; from Lansing 1991:119).

actual pattern of water temple control achieves the highest rice yields by optimizing the trade-off between water sharing and pest control, as shown in Figure 6.

On the far right in Figure 6, when the cropping pattern is set by each individual subak, there is high pest damage. On the far left, a single cropping pattern for the whole watershed reduces pest damage but maximizes water stress. The highest peak is achieved by the scale of coordination that most closely approximates the temple scale of coordination. These results suggest two initial conclusions: (1) most of the observed variation in harvest yields is explainable by reductions in yields caused by water stress or pest damage (Figure 5); and (2) the scale of social coordination in the management of irrigation has important effects on both of these variables (Figure 6; Kremer and Lansing 1992b).

Modeling Adaptation on a Rugged Fitness Landscape

These results encouraged one of us (Lansing) to shift his attention from the mechanisms at work at the level of individual water temples, to the possible existence of system-level properties of temple networks. Our approach to this question borrows from the theory of "fitness landscapes" in biology (Wright 1932; Palmer 1991; Kauffman and Johnsen 1991). As we have just seen, it is possible to calculate theoretical optima for rice production, and then compare these results to the actual system of temple coordination along

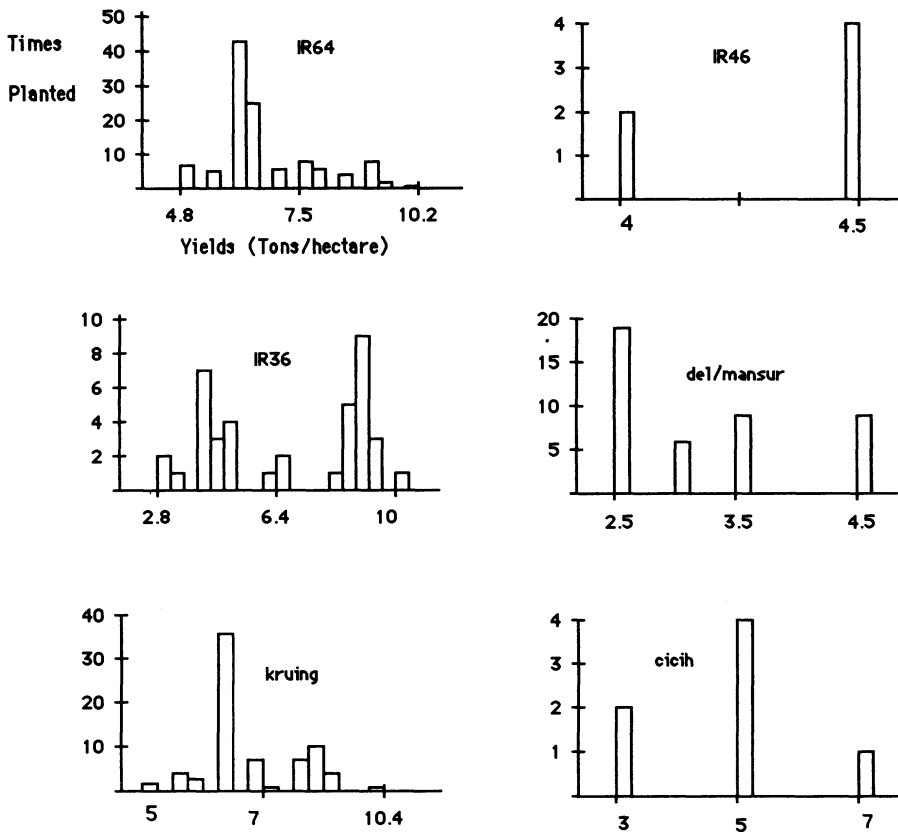


Figure 4

Distribution of rice harvest yields (tons/hectare) for six varieties planted in 1988–89.

each river. In biology, the idea of a fitness landscape is based on the notion that the fitness of an organism (species, population) depends not only on its own intrinsic characteristics (“genotype”) but also on its interaction with a local environment. The term “landscape” comes from visualizing a geographical landscape of fitness “peaks,” where each peak represents an adaptive solution to a problem of optimization. Figure 6 may therefore be viewed as an example of a fitness landscape, in which the highest fitness peak is achieved by the temple scale of coordination. Note, however, that in biological models optimization occurs through “blind” natural selection, whereas here we propose a different mechanism: the deliberate efforts of farmers to cooperate in setting cropping patterns so as to maximize their harvests.

But it was not yet clear from our earlier analysis how the temple networks manage to find an optimal scale of coordination in the management of irrigation. Are differences in the structure of temple networks from one river to the next the result of deliberate planning by farmers, priests, or royal engineers? Or are they the product of trial-and-error adjustments by generations of farmers? Could the water temple network of River A do as well managing River B, or is each temple network a uniquely optimal solution to the specific ecological conditions of a particular region? And, finally, how do temple networks respond to changing conditions?

A different type of simulation analysis provides a way to investigate such questions, which relate to the dynamic behavior of temple networks. Kremer’s model (described above) became a single time-step in a program developed by Lansing to explore the pro-

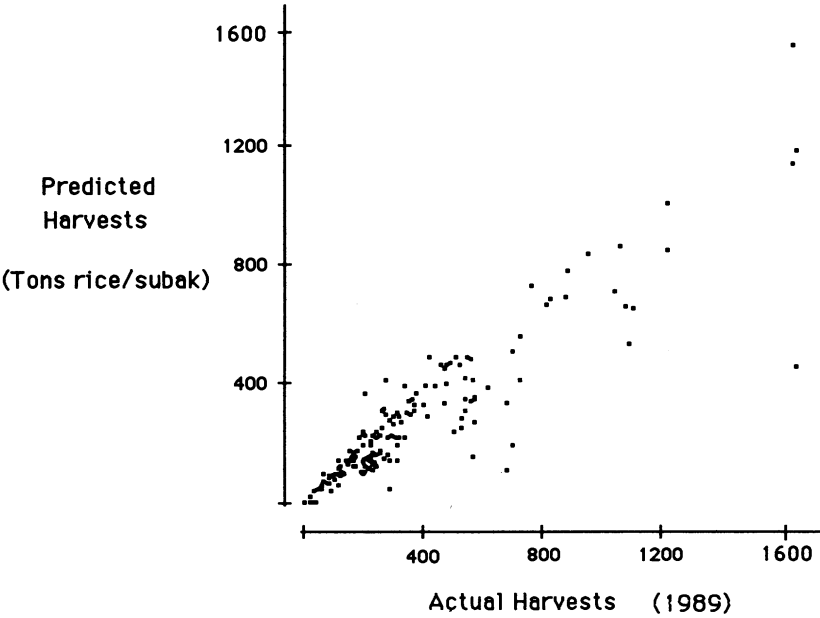


Figure 5
Comparison of model predictions with actual rice harvests by subak (1989). Pearson's product-moment correlation $r = .90$ (from Kremer and Lansing 1992b).

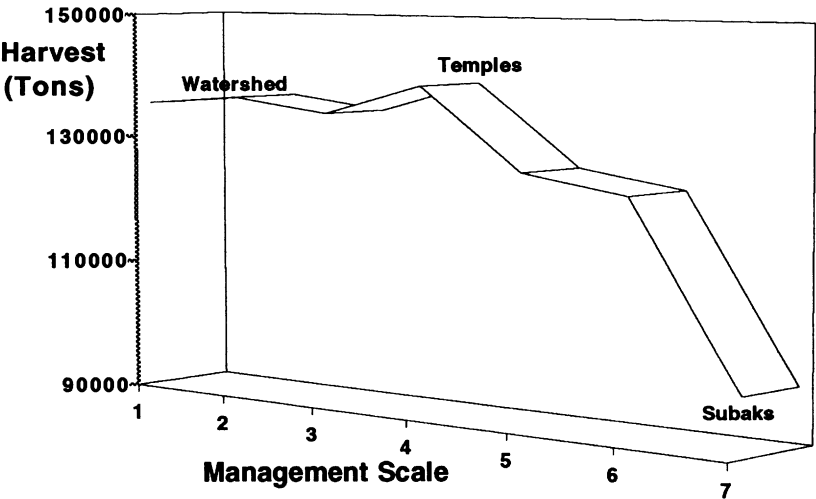


Figure 6
Effects of seven different scales of social coordination on rice yields, pest damage, and water stress.

cess of adaptation on a changing fitness landscape. Imagine that the water temple system does not exist, but that all the known ecological conditions remain unchanged along both rivers. As a new year begins, each of the 172 subaks in the model begins to plant rice or vegetables. At the end of the year, harvest yields are calculated for each subak. Subse-

quently, each subak checks to see whether any of its neighbors got higher yields. If so, the target subak copies the cropping pattern of its (best) neighbor. The model then simulates another year of growth, tabulates yields, and continues to run until each subak has reached its local optimum. What will happen?

Figure 7 shows the results of such a simulation for the traditional Balinese cropping pattern, *kerta masa*. This cropping pattern begins with a long-maturing rice variety (del or mansur), followed by a fallow period, and a faster-maturing second rice crop (cicih). In this simulation, all subaks follow this cropping pattern. However, starting dates (when to begin planting the first crop) are randomly assigned to each subak.

After the first run, the average yield (tons rice/hectare/year) for the subaks was slightly more than 5 tons. Each subak then compared its yield with those of its four closest neighbors. Eighty-six subaks discovered that one of their neighbors had a higher yield, and copied their neighbor's cropping pattern. The next year, average yields went up dramatically, and 94 subaks changed their cropping patterns. After eight years, average yields peaked, and all but 20 subaks stopped changing their cropping patterns. One hundred and fifty-two subaks had reached a local optimum, in which their yields would not improve if they adopted a neighbor's cropping pattern. The remaining 20 subaks keep swapping cropping patterns with their neighbors indefinitely, as first one and then another obtains a slightly better yield.

Figure 8 maps the distribution of cropping patterns for subaks in the first run, and Figure 9 in the last run of the simulation; Figure 10 maps the pattern of coordinated cropping patterns achieved by the water temple network. The resemblance between the last run of the hill-climbing program (Figure 9) and the temple system (Figure 10) is evident. Competition to achieve maximal yields led to the formation of cooperative units with synchronized cropping patterns that bear a very close resemblance to actual water temple networks.

Should we therefore conclude that patches of coordination resembling water temples will spontaneously develop as subaks seek to optimize their harvest yields? It is worthwhile to note that the number of possible distributions of cropping patterns that could occur in this model is astronomically large, and the chances that a temple-like system of coordination would occur by chance are correspondingly small. But perhaps the temple networks are uniquely fitted to the traditional cropping pattern as a result of centuries of trial and error by the subaks? To test this possibility, many more simulations were conducted in order to vary not only the cropping patterns (crop varieties and start dates), but also the ecological parameters (rainfall, evapotranspiration, pest growth rates, dispersal rates, and damage coefficients). The same pattern occurred in all cases: after 8–35

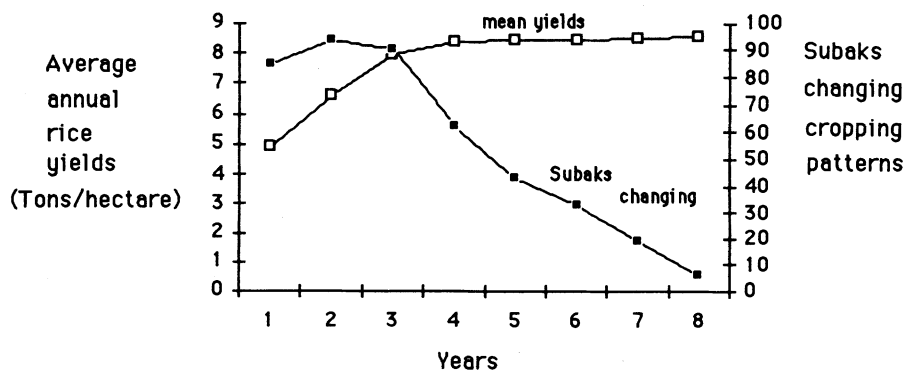


Figure 7
Increase in average rice yields as artificial temple networks appear.



Figure 8

First run of a model of coadaptation. Each symbol indicates a different cropping pattern, randomly distributed among subaks in the Oos-Petanu watersheds. Average harvest was 4.9 tons rice/ha.

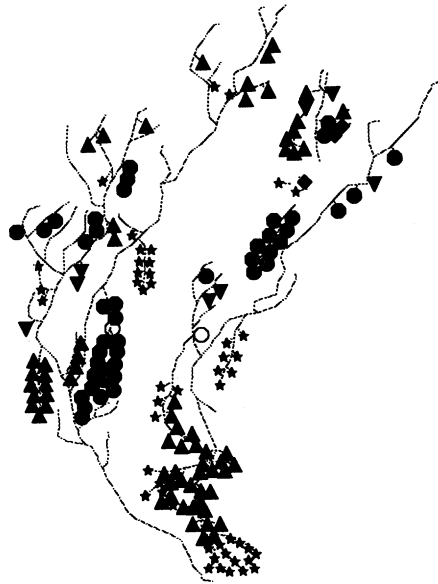


Figure 9

Last run of the model; average harvest rose to 8.57 tons/ha.

years, a complex structure of coordinated cropping patterns emerged, which bore a remarkable similarity to the actual pattern of water temple coordination along these rivers.

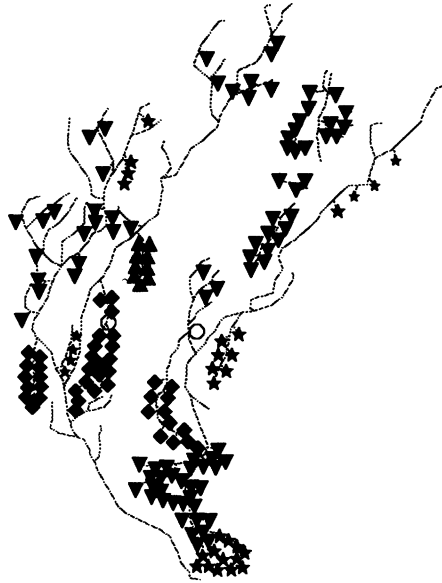


Figure 10

Distribution of synchronized cropping patterns in the traditional system of water temple networks.

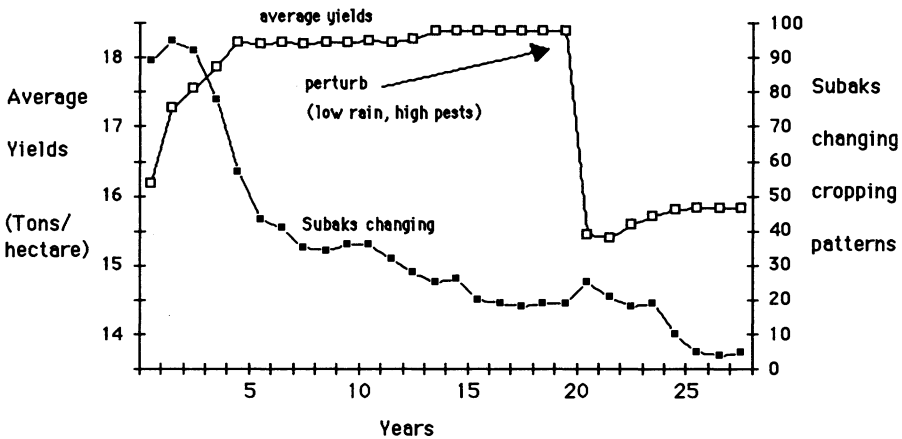


Figure 11

Effects of perturbation on yields.

Finally, consider the outcome of an experiment in which the network is perturbed: Figure 11 shows the results of a simulation in which each subak grew two crops of high-yielding rice, as well as a vegetable crop. Using normal values for all ecological variables, average yields improved from 16 to 18.5 tons/hectare/year after 20 years, and stabilized with 20 subaks still changing their cropping patterns. In the 21st year a plague of pests was visited on the region by increasing the pest growth, dispersal, and damage rates. Simultaneously, rainfall was decreased to 80% of normal. Yields fell to 15.3 tons/hectare/year immediately but recovered to 15.8 within 7 years. Yet when the conditions of low

rain and high pests occurred from the very beginning of an otherwise identical simulation, it took twice as long to reach the same optimal yield value.

Discussion

Before pursuing the implications of these results, it is worthwhile to linger for a moment over the mathematical logic that produced them. In the sequences of simulation runs described above, each subak alters ecological conditions for its neighbors when it varies its cropping pattern. A coadaptive process begins as each subak responds to these changing conditions by seeking to optimize rice yields. The actions of the subaks affect conditions for their neighbors, and the fitness landscape changes for most subaks with each run of the model. In other words, the actions of the subaks influence ecological variables such as irrigation flows, which in turn affect future decisions by other subaks. For example, Figure 12 shows differences in water shortages at one of the 12 major irrigation systems in the model (Klutug) for a typical simulation. Major water shortages in March and April, which led to reduced yields for some subaks in the early runs, have disappeared by the 54th run. A similar pattern always occurs at the other 12 weirs: water shortages are gradually reduced. Note that this coadaptive process does not find the ideal cropping pattern for all; rather, it finds locally optimal scales of coordination in the synchronization of cropping patterns. Let us call these artificial water temples, to distinguish them from real water temples. The interesting result here is that the same phenomenon occurs every time, regardless of the initial distribution of cropping patterns, or ecological parameters such as flow rates or pest biology. Within 8–35 years, depending on ecological conditions, the subaks spontaneously self-organize into a network of artificial water temples where all subaks are at or near a local optimum.

Once this structure appears, the entire network displays an interesting emergent property: the ability to recover from external perturbations (such as low rainfall or high pest levels), as shown in Figure 11. Such disturbances initially generate a cascade of changes that propagate through one or more clusters of subaks, but soon lead to a new equilibrium. The ability of the system as a whole to react to changes is thus a property of the network itself, rather than the accidental consequence of the actions of individual subaks or temples. Put another way, the ability of each local group of farmers to reclaim the

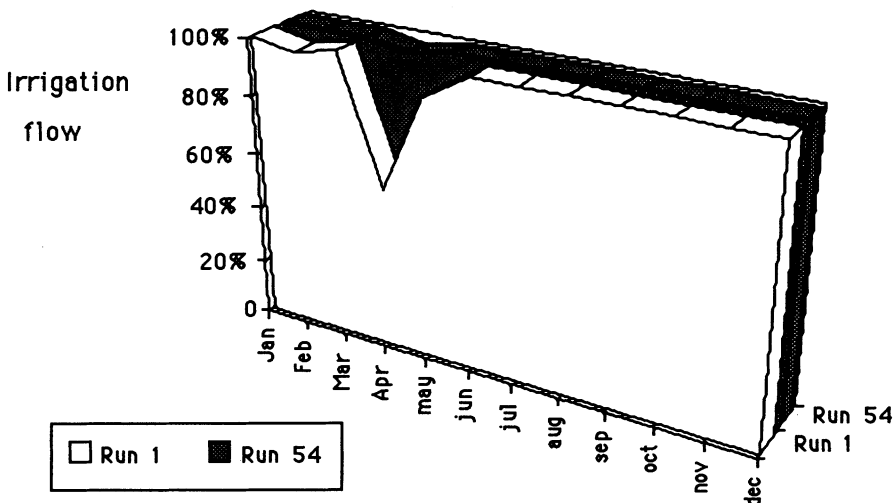


Figure 12
Water shortages at the Klutug dam.

shifting peaks of the fitness landscape depends not only on their own initiative, but on the ability of the system as a whole to respond to changes.

Recent work in the mathematical theory of optimization on rugged fitness landscapes sheds an interesting light on this process, suggesting that these results are not artifacts of our computer program, but predictable outcomes from a process of coadaptation on a rugged fitness landscape. Both of the properties we have noted—the maximization of sustained yields and the enhanced ability of the entire network to cope with perturbations—appear to occur for a wide range of coevolving complex systems. Artificial water temple networks fulfill the formal definition of a *complex adaptive system*:

(i) It consists of a network of interacting agents (processes, elements); (ii) it exhibits a dynamic, aggregate behavior that emerges from the individual activities of the agents; and (iii) its aggregate behavior can be described without a detailed knowledge of the behavior of the individual agents.

An agent in such a system is adaptive if it satisfies an additional pair of criteria: the actions of the agent in its environment can be assigned a value (performance, payoff, fitness or the like); and the agent behaves so as to increase this value over time. A complex adaptive system, then, is a complex system containing adaptive agents, networked so that the environment of each adaptive agent includes others in the system. [Holland and Miller 1991:365]

If each agent (in this case, each subak) always acts independently, the system as a whole behaves chaotically. Alternatively, if each agent is linked to all the others, the system is stable but only massive perturbations can cause alterations in behavior. Metaphorically, the system is frozen into place. Complex behaviors occur when these frozen components begin to “melt,” and different-sized islands of synchronized agents emerge. This transitional state between order and chaos is the narrow zone of complex or periodic behavior (Langton 1991; Weisbuch 1991). Recent work in the theory of complex systems suggests that coevolution on a rugged fitness landscape may drive many kinds of networks toward this zone or class of behaviors. As the biologist Stuart Kauffman recently observed, “as if by an invisible hand, coevolving complex entities may mutually attain the poised boundary between order and chaos. Here, mean sustained payoff, or fitness, or profit, is optimized” (Kauffman 1993).

By now we have come a long way from our original point of departure, and it may be helpful to say a few concluding words about the relationship between the models described here and evolutionary ecology. One major difference is the level of analysis: evolutionary ecology focuses on determining the fitness value or payoff of specific strategies for individuals, whereas from a systems perspective we are interested in whether it is possible to predict changes in these values over time by analyzing the interaction of social and ecological variables. Our model tracks the behavior of 172 subaks along two rivers, each of which sets an annual cropping pattern (rice, vegetables, fallow interludes). In the model, for $i = 1$ to N cropping patterns: x_i = frequency of cropping pattern i ; f_i = fitness payoff (yield, expressed as tons rice/hectare/year); and f_{opt} = a local optimum fitness value.

In the first year, we calculate the fitness payoff (yield) for each cropping pattern, f_i . In succeeding years, x_i varies as its fitness value changes with respect to the average fitness (\bar{f}). For each cropping pattern tested:

$$\dot{x}_i = f_i - \bar{f}$$

where

$$\bar{f} = \sum_{i=1}^N f_i / N$$

As time goes on, and patches of coordinated cropping patterns appear which improve the balance between water sharing and pest control, the mean fitness level of the entire system increases:

$$\bar{f} \rightarrow f_{opt}$$

A three-dimensional illustration of this process is shown below in Figure 13. Ultimately, regardless of the initial choice of cropping patterns, the mean value \bar{f} increases to a local optimum after artificial water-temple networks come into existence. For example, compare the average yields for the initial and final runs with three different cropping patterns in Table 1.

While evolutionary ecology also begins with the concept of fitness (f_i), it makes different assumptions about how these values are found. The key issue is the process of selection: as Eric Smith observes, “in evolutionary ecology adaptation via natural selection in a finite environment is the primary causal force” (1984:67). Natural selection is thus obliged to try out most of the possible variants (Eigen 1992:27). In our model, we could mimic this process by randomly changing cropping patterns for each subak every year and selecting good ones only as they appear, a procedure that would take a very long time, even on a computer. Instead, we try to model the effects of deliberate selection, in this case the annual meetings of the subaks, where the farmers discuss the outcomes of last year’s cropping patterns in their vicinity and try to pick a good one for the next cycle. In mathematical terms, they are searching the peaks of their local fitness landscape. This process of selection is not blind, but on the contrary highly efficient.

A second key distinction is the change in the fitness landscape itself brought about by this search strategy. As we have seen, the emergence of artificial temple networks in-

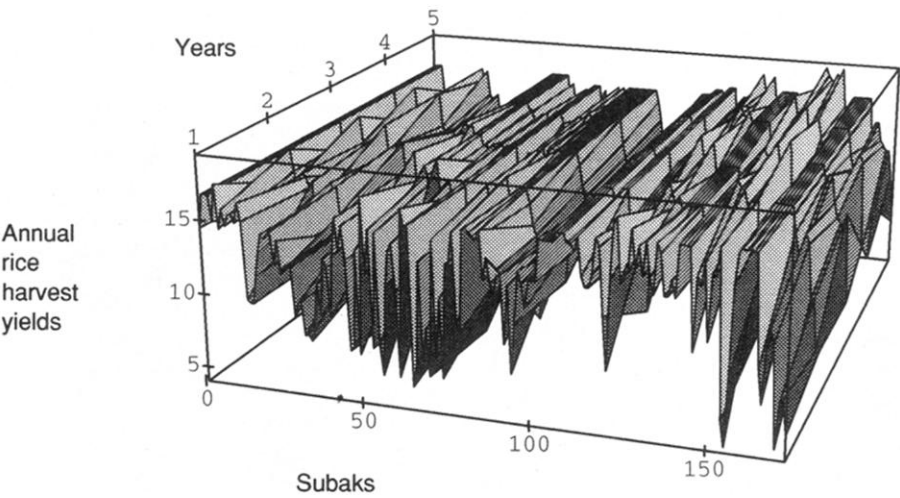


Figure 13
First five years of a hill-climbing simulation of the Oos-Petanu watersheds. Yields change every year for most subaks, in a process of coadaptation.

Table 1
Increase in mean fitness (\bar{f}) after temple networks appear.

	Cropping patterns		
	Traditional	High-yielding	Low rain, high pests
First run	4.9	15.91	13.67
Last run	8.57	18.08	17.66

creases the height of the fitness peaks, an effect that occurs regardless of our initial assumptions about the physical and biological systems. Our model demonstrates that cultural systems like the water temple networks can have macroscopic effects on the topography of the adaptive landscape. But such effects are not apparent from within the horizons of evolutionary ecology, since they are properties of systems rather than individuals.

Conclusion

The analytic techniques described in this article have enabled us to shift the level of analysis progressively from the individual farmer and field to the subak and water temple, and ultimately to the historical development of temple networks. We have shown that the structure of water temple networks could have developed through a process of spontaneous self-organization, rather than deliberate planning by royal engineers or other planners. This idea could be subjected to a more rigorous test, since our methodology is capable of predicting the response of temple networks to historical changes. The resulting patterns of spatial organization could be compared with the actual sequence of development as revealed by archeological investigations.

We have also shown that the emergence of temple networks leads to higher average harvest yields, and improvement in sustainability (the ability to cope efficiently with ecological perturbations). Since these effects occur in our model as consequences of a process of coadaptation, they are probably not unique. Balinese water temples may be representative of a class of complex adaptive systems that have evolved to manage agroecosystems. As Roy Rappaport argued a generation ago, it is likely that ritual often plays an important role in such "traditional" systems of resource management (Rappaport 1971).

It also follows from our analysis that the wide range of harvest yields reported by the subaks for 1988–89 (Figure 4) is likely to be the signature of suboptimal conditions, in which the subaks are prevented from rediscovering an optimal distribution of cropping patterns. In other words, under present conditions new crops and cropping patterns are tried out each year, in an effectively random process. Some subaks do well, others poorly, and the network as a whole remains in a state of continuous perturbation, corresponding to the early runs in our simulation model. As we have argued elsewhere, these conditions are aftereffects of the Green Revolution in Bali: the replacement of native Balinese rice varieties with high-yielding imported varieties, coupled with new management plans based on the assumption that production will be optimized if each farm or subak is an autonomous productive unit (Lansing 1991). Our results suggest, to the contrary, that self-organizing temple networks are intrinsically capable of a better job of water management than either autonomous subaks or centralized hierarchical control (Figures 8–10). But as long as research on agroecosystems remains focused on the behavior of individuals, the productive role of "traditional" systems of resource management such as the water temples will remain invisible. Ironically, recent plans for the improvement of Balinese irrigation systems by international development agencies foresee an end to the productive role of water temples "as an almost inevitable result of technical progress" (Asian Development Bank 1988:47).

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