Report

Regime Shifts in Balinese *Subaks*

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Ecosystems may undergo nonlinear responses to stresses or perturbations. Hence there can be more than one stable state or regime. It is not known whether alternate regimes also occur in coupled social-ecologica-l systems, in which there is the potential for intricate feedbacks between natural and social processes. To find out, we investigated the management of rice paddies by Balinese farmers, where ecological processes impose constraints on the timing and spatial scale of collective action. We investigated responses to environmental and social conditions by eight traditional community irrigation systems (*subaks*) along a river in Bali to test the intuition that older and more demographically stable *subaks* function differently than those with less stable populations. Results confirm the existence of two attractors, with sharply contrasting patterns of social and ecological interactions. The transition pathway between the two basins of attraction is dominated by differences in the efficacy of sanctions and the ability of *subaks* to mobilize agricultural labor.

The relationship between the social and natural worlds is a perennial question in anthropology and more broadly in the social and environmental sciences. But the methods of social scientists and ecologists are not easily combined. Most research on cooperation, public goods, and collective action problems is organized around ideas of stability. Both microeconomics and evolutionary game theory are equilibrium theories, which examine the properties of various fixed points and analyze the conditions under which they are selected. In contrast, studies of ecosystem dynamics, especially long-term ecological research, suggest that ongoing change and variability are typical (Carpenter et al. 2011; Dearing et al. 2012; Gutierrez, Hilborn, and Defeo 2011; Holling 1973; Liu et al. 2007; Scheffer et al. 2009). Nonlinear transitions between alternate stable states are characteristic of lakes and rangelands, and there is growing evidence that these occur at all scales up to the planetary (Barnosky et al. 2012).

Consequently, combining linearized equilibrium models of cooperation or collective action with nonlinear dynamical models of ecosystems, in what are called "coupled social-ecological systems" (SES), creates a mismatch. Equilibrium theories assume that any given combination of state variables will produce a unique result. But in a coupled SES, in which both social and ecological components may interact nonlinearly, it is possible that alternate steady states exist (Biggs et al. 2009; Folke 2006). If we are only looking for a single equilibrium, evidence of alternate steady states will be mistaken for noise.

This point was brought home by the discovery of alternate stable states in Dutch lakes. For decades, excess fertilizer flowed into the lakes, triggering algae blooms and eutrophication. But simply reducing the amount of fertilizer entering the lakes was not enough to restore them to clarity. It turned out that alternate stable states existed, one turbid and the other clear. In ecology, such alternate stable states are known as "regimes." The effects of nutrient flows depended on which regime a lake was in, so generalizing across all lakes obscured these differences. But once the existence of alternate regimes was recognized, a simple intervention was sufficient to restore the lakes to health. Temporarily removing the fish allowed sediment to settle and zooplankton populations to increase, whereupon water clarity could be improved by reducing the amount of fertilizer flowing into the lakes (Attayde et al. 2010).

But what of more tightly coupled SES, where there is the potential for intricate feedback between natural and social processes? Rice paddies, for example, are shallow artificial lakes that are brought into existence by the collective action of groups of farmers. While the farmers are nominally in control, ecological processes impose constraints on the timing and spatial scale of collective action required to sustain the rice crop (Lansing 2006). Paddies must be flooded and drained to deliver nutrients and promote plant growth, while also controlling weeds and rice pests. Synchronized harvests can reduce pest populations by removing their habitat, but for this to work, the extent of the fallow period must be large enough to prevent the pests from migrating to fields that are still in cultivation (see supplement A, section 1.1, available online). Historians have long argued that under such conditions, landscapes and institutions will co-evolve. Is this a simple linear process? Or do nonlinear transitions occur in what one historian calls "the reciprocal influences of a changing nature and a changing society" (White 1985:335)?

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To find out, we investigated the interaction of social and ecological processes in an ancient and extensively studied system of wet-rice irrigation, the *subaks* of Bali (Lansing 2006, 2007 [1991]). *Subaks* are traditional, community-scale institutions that manage irrigation water and planting schedules. Balinese farmers regard water as the gift of a goddess, and *subaks* are entrusted with the fair and equitable use of her gift for the purpose of growing paddy rice. *Subaks* have existed at least since the eleventh century (Goris 1954); today there are approximately 1,000 (Lansing et al. 2009). From one year to the next, they must adjust to changing environmental and social conditions. This requires ongoing collective action, which typically includes a heavy burden of ritual obligations as well as agricultural labor. Too little investment could cause crop losses, angry neighbors, or indeed the wrath of the gods, but too much might incur the wrath of one's family. Ethnographic observations suggest that *subaks* vary in their ability to increase or decrease these investments, as conditions require (Lansing 2006). When this capacity declines, the *subak* becomes vulnerable. But failures in cooperation may be temporary; crop losses may prompt a return to high investments in the *subak*. Thus, while low investment could mean that a *subak* is close to collapse, it could also mean that the farmers are enjoying a period of low stress, which may or may not be temporary. This study was designed to test the intuition that as a result of their different histories of local adaptation, the older and more demographically stable *subaks* respond more effectively to both environmental and social challenges than *subaks* with less shared history.

Subaks are particularly well suited to the analysis of coupled social-ecological interactions for three reasons. First, they are functional institutions: the economic welfare of traditional Balinese rice-growing villages is largely dependent on their efficacy. Second, the time lag between failures in cooperation within the *suba*k and perceptible consequences is short due to the small scale of *subak* irrigation, the fragility of terraced fields, and the potential for crop losses from pests or water shortages. Hence there is a strong potential for social learning and adaptation. Third, there is large variation in relevant variables, such as the age of *subaks*, their demographic composition, and local environmental conditions: for centuries, *subaks* have evolved independently in neighboring catchments. Based on 30 years of ethnographic observations (Lansing 2007 [1991]), we predicted that independent of environmental conditions, pro-social behavior would be more common in *subaks* where nearly all families share a long history of managing their rice terraces, bringing with it a heightened awareness of the consequences of failure.

We tested this hypothesis in a comparative study of eight *subaks* located along the Sungi river in the district of Tabanan, the largest rice-growing region in Bali (fig. 1). In the rainy season, rivers flowing down steep Balinese volcanoes are hard to control with traditional engineering techniques; consequently, the older *subaks* tend to be located upstream, where the smaller flows are easier to manage. One of the earliest dated royal inscriptions is kept in a temple near the headwaters of the Sungi and contains references to wet-rice agriculture and nearby streams (Babahan 1, 947 AD; in Goris 1954). Newer and larger *subaks* and irrigation systems are located along the lower stretch of the river; they cannot be dated as precisely but were probably constructed beginning in the eighteenth century (Schulte 1996).

Method

Analysis of this model system began as a follow-up to a prior study that used neutral genetic markers to investigate the demographic histories of 21 *subaks* in different regions of Bali (Karafet et al. 2005; Lansing et al. 2008). The data collected for the eight Sungi river *subaks* were reanalyzed to discover whether there are significant differences between the demographic histories of the upstream and downstream *subaks* (supplement A, section 1.2). The methods used for the genetic analysis are fully described in Karafet et al. 2005; here we summarize the key points (supplement A, section 1.3). Genetic samples were obtained from farmers in the 8 *subaks* along the Sungi river ($N = 120$), as well as 13 *subaks* located elsewhere in Bali ($N = 287$), and a geographically distributed sample of 180 other Balinese men to provide context for the genetic patterns observed in the *subaks*. Results of this prior study showed that older rice-growing isolated villages typically have less genetic diversity than elsewhere on the island, reflecting the cultural preference for endogamous marriages within these villages, along with very low rates of in-migration. Newer villages, or those with more in-migration, show greater diversity.

To discover whether upstream *subaks* vary systematically from downstream *subaks* in their responses to social and environmental challenges, two methods were used: a survey of farmers in each *subak* ($N = 83$) and an experimental game ($N = 43$). For the survey, in each of the 8 *subaks*, 10 or more randomly chosen farmers were invited to answer a questionnaire administered by one of us who speaks Balinese (Lansing), assisted by local agricultural extension agents assigned to each *subak*. Farmers who participated were paid the equivalent of a laborer's day wage (30,000 Indonesian rupiah). Survey questions were divided into two sections. The first section asked farmers about their harvest yields for the past 2 years and whether they experienced losses due to water shortages or pest infestations. They were also asked how much farmland they owned or sharecropped over the same time period. The second section asked for the farmer's opinions about factors that affect the *subak*'s ability to respond to both social and environmental problems. These included the effectiveness of sanctions against norm violators; the ability of the *subak* to mobilize collective labor for maintenance of the irrigation works and the performance of temple rituals; the general condition or state of their *subak* and its capacity to cope with either technical or social problems. The farmers were also asked about the effects of differences in caste and

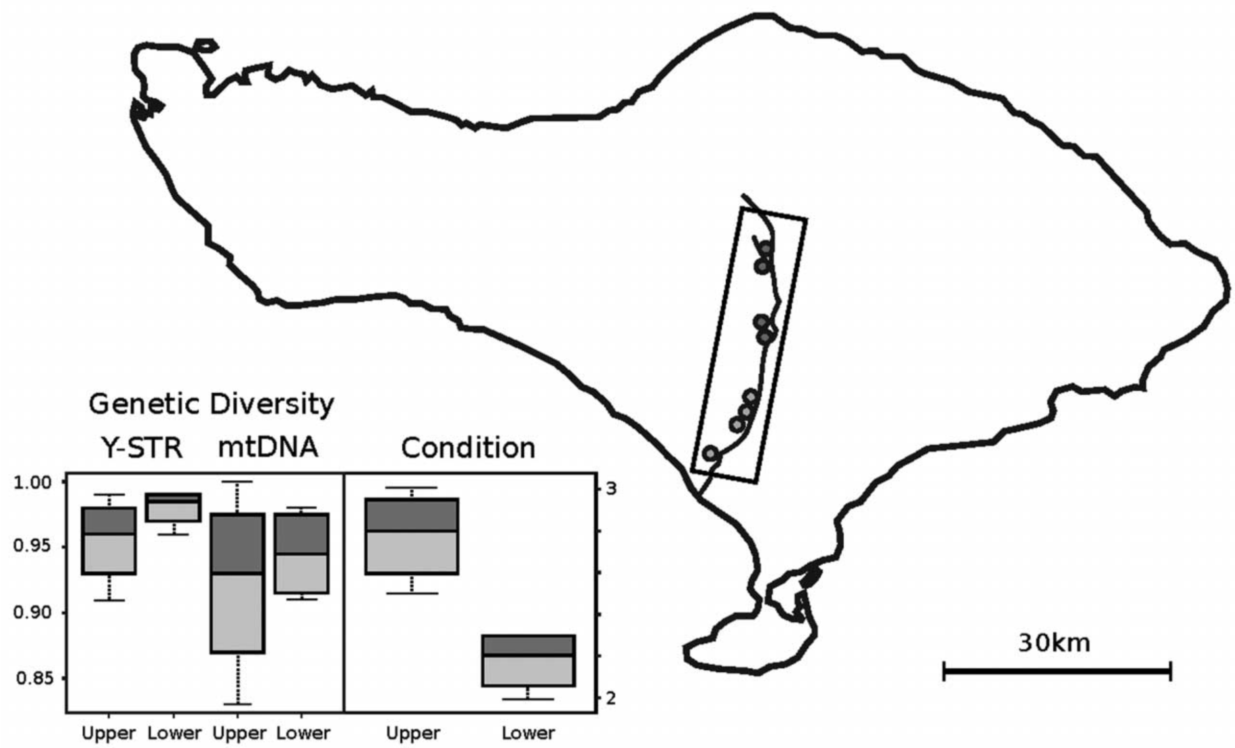

Figure 1. Map of Bali showing the eight *subaks* in this study, on the Sungi river. All four of the upstream *subaks* and two of the downstream *subaks* are small (mean size 67 ± 16 farmers), the other two downstream *subaks* are much larger (231 and 535 members). Left histogram: mean Y-STR genetic diversity: 4 lower *subaks* 0.980, 4 upper *subaks* 0.955; mean mtDNA diversity: lower *subaks* 0.945, upper *subaks* 0.923, $P = .031^*$. Right histogram: responses of 10 farmers in each subak to "What is the overall condition of your subak?" Mean lower *subaks* 2.150, upper *subaks*: 2.775, P$ < $4.993 e-10***. A color version of this figure is available online.

class on the functioning of their *subak*. Because rivalry between castes is endemic in Bali, the proportion of high versus low caste members in each *subak* could affect its ability to respond to problems. Similarly, farmers were also asked to assess the effects of class differences (indexed by the proportion of sharecroppers vs. landowners in the *subak*) on the efficacy of their *subak* (supplement A, section 1.5).

To facilitate comparisons of pro-social behavior both between *subaks* and with other common property regimes, the same farmers who answered our survey questions also played the Dictator Game. In this simple game, each player was given another day's wage and told that he could share as much or as little as he chose with another member of his *subak* who was present at the time. Players were assured that the identity of both givers and receivers would be kept confidential. The purpose of this game was to see whether the range of anonymous gifts ("offers") to members of one's *subak* varies between *subaks*.

Because of the guarantee of confidentiality, data on offers in the game and genetic data were aggregated at the scale of *subaks*, while survey data was tabulated at the level of individual farmers (supplement A, section 1.6). Survey results were analyzed using multivariate ANOVA and principal component analysis at three scales: the whole system of 8 *subaks*, each individual *subak*, and two clusters (upper and lower *subaks*). Contrasting patterns of correlation appeared in the two clusters, which cancel each other out at the scale of the whole system (supplement A, section 1.7). To gain insight into how *subaks* might transition from one regime to the other, basins of attraction were calculated from the survey data, and the most probable transition path between them was calculated with an interpolation approach (supplement A, section 1.8).

Results

The genetic diversity of maternal and paternal lineages is significantly reduced ($P = .031$) in the four upper *subaks* relative to lower *subaks* (fig. 1). These results suggest that the upstream *subaks* are more demographically stable; for example, they have a long history of continuous occupation by the same families. All *subaks* experienced both water shortages and pest damage to varying degrees. Water shortages were perceived to be a greater problem by upstream *subaks*, while pest infestations

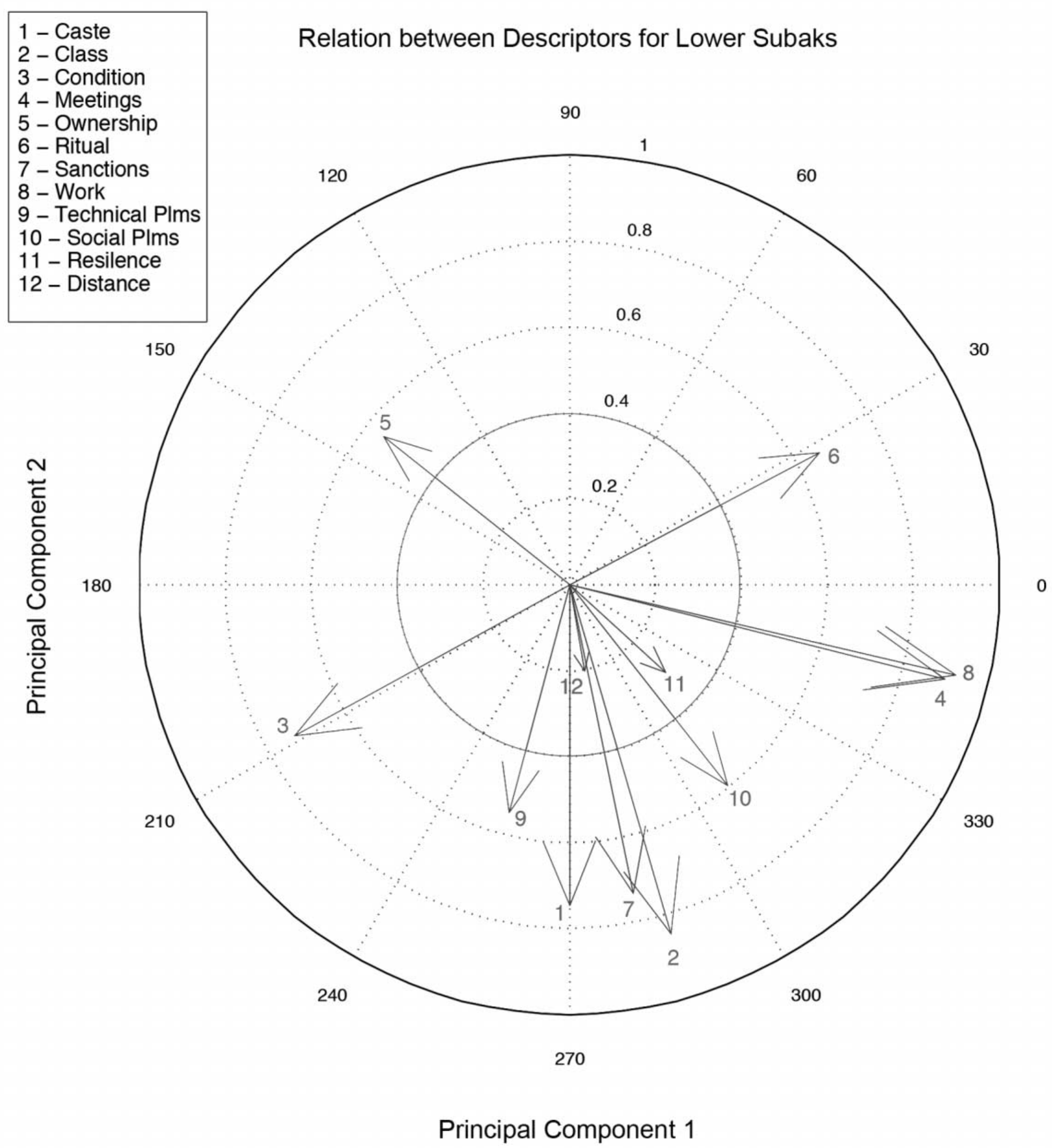

Figure 2. Biplot of lower 4 *subaks* showing the correlation structure of responses to the surveys. Descriptor axes extending beyond the equilibrium circle in red are significant. For reference, here and in fig. 3, the axis of no. 1 (effects of caste differences) points at 270°. Here "ownership" (no. 5, the proportion of sharecroppers vs. farm owners) anticorrelates with no. 10, the ability of the *subak* to resolve social problems. The first and second principal components explain nearly all of the variance (PC1-92.0%, PC2-2.4%), so the correlation matrix is nearly flat and sharply contrasts with the lower *subaks* in fig. 3. A color version of this figure is available online.

were perceived to be more problematic by downstream *subaks* ($P = .032$). This difference was also noted by the agricultural extension agents who assisted with the surveys. In the most recent harvest (2010), average rice harvests were slightly larger in the upstream *subaks* (5.42 tons/hectare) than downstream (4.83). *Subaks* also experience problems stemming from social conflicts, which may be affected by tensions stemming from differences in either caste or social class. In our survey, *subaks* varied in the proportion of their members who belong to the upper castes (0%–24%). Comparative analysis of the effects of class differences were facilitated because the mean proportion of owners versus sharecroppers (no. 5, "ownership") is virtually identical for the two groups (upper *subaks*: mean 75.2%, SD 40%; lower *subaks*: mean 78.2%, SD 34%; $N = 83$).

Farmers in the upper *subaks* responded more positively than downstream farmers to all survey questions, including

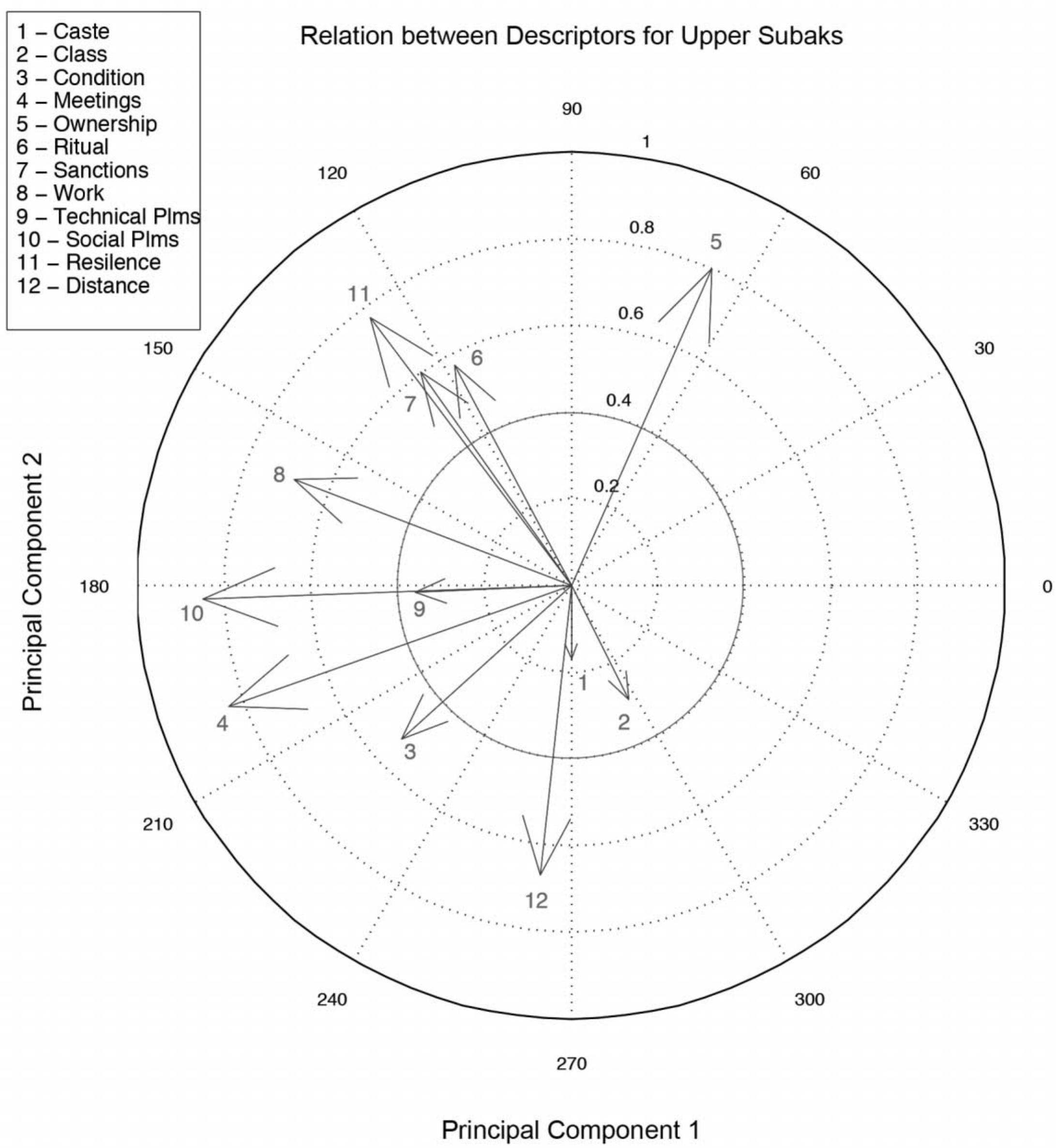

Figure 3. Biplot of upper 4 *subaks*. Most variables have different effects than in the lower *subaks*. For example, there is no relationship between no. 5, the proportion of sharecroppers vs. owners, and no. 10, ability to resolve social problems. Here also the first two principal components explain most of the variance (PC1-85.5%, PC2-5.4%). A color version of this figure is available online.

the efficacy of sanctions; the ability of the *subak* to mobilize to carry out irrigation maintenance, perform rituals, and conduct meetings; and the overall condition and resilience of the *subak* (Pillai's trace of rank scores = 0.49, $P = .000029$). Principal components analysis of the 11 variables included in the surveys showed sharply contrasting patterns (figs. 2, 3). Nearly all of the variance in the two correlation matrices is accounted for by the first two principal components. The differences in survey responses shown in figures 2 and 3 suggest that social and ecological variables have different effects in the upper and lower *subaks*. To assess the significance of these differences, we examined the location of each *subak* in the principal component space defined by the two dominant eigenvectors. The upper and lower *subaks* form two clusters, each of which we associate with a well on some free energy surface, with a minimum that is locally harmonic. Figure 4 shows the attractor basins for the two regimes. Here the length and orientation of the axes are defined by their orientation in the 11-dimensional principal component space from the survey data (supplement A, section 1.8). Notably, we observe from figure 4 that the upper and lower regime ellipses do not intersect each other.

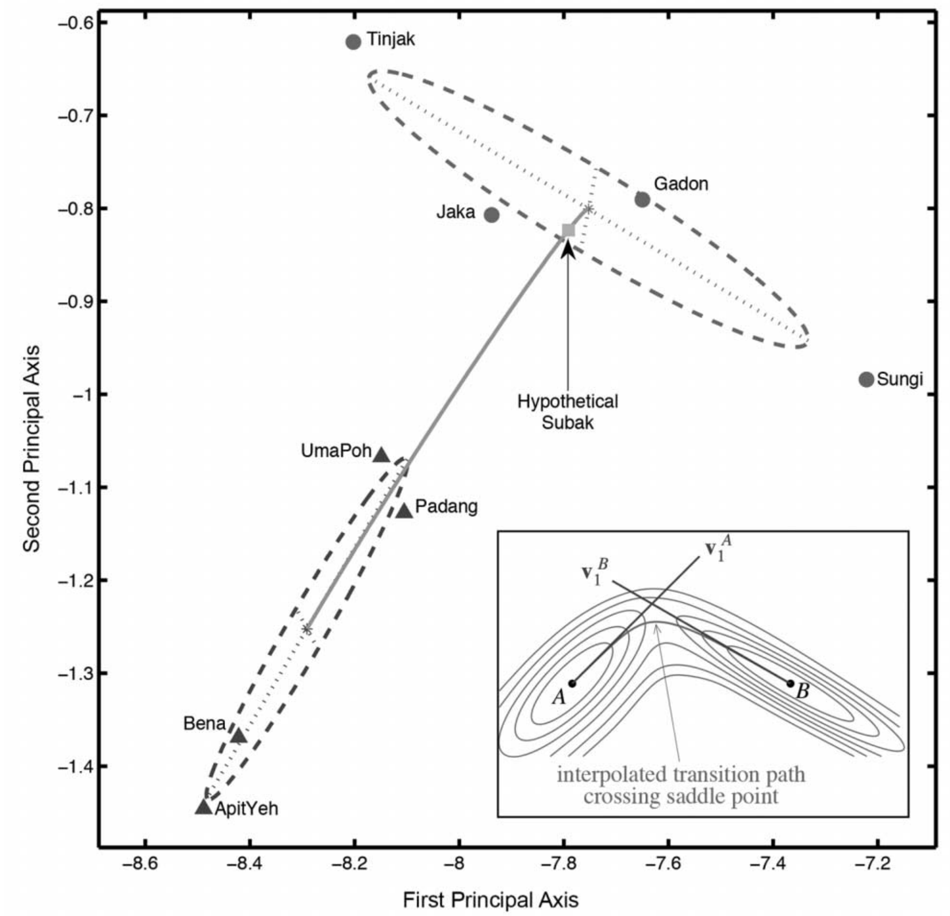

Figure 4. Ellipsoids depict the potential wells within the 11-dimensional principal component space based on the survey data. Because nearly all of the variation in the survey results is explained by the first two principal components, the patterns of interaction among the variables are nearly linear within each of the two basins. But the correlation matrices are significantly different in each basin; note that they do not intersect. The green line indicates the most probable transition pathway for a hypothetical *subak* undergoing a transition between basins. Globally, the variables that dominate the transition pathway are condition of the *subak* (30%), efficacy of sanctions (14%), and ability of the *subak* to mobilize labor (10%). A color version of this figure is available online.

Finally, offers (gifts) in the Dictator Game were more generous in the upstream *subaks* (mean 33.75%) than the downstream *subaks* (mean 25.5%, $P = .047$, Welch *t*-test). The size of the gifts varied with the farmer's estimate of the overall state of their *subak*, but the nature of this relationship varied between the two groups. Among the downstream *subaks*, the worse the condition of one's *subak*, the smaller the offer. The opposite pattern emerged in the upstream *subaks*: the worse the state of one's *subak*, the more generous the offer. These correlations have opposite effects, so at the level of the global system of eight *subaks* there was no correlation.

Discussion

Responses of these eight Balinese communities to social and environmental challenges fall into two contrasting patterns. The upstream and downstream groups experience similar social and environmental conditions, but they respond to them in different ways. Intriguingly, this contrast reappears in the results from the Dictator Game. The average offer in the Dictator Game for the entire sample of farmers was 30% with a large variance, at the low end of the scale of offers in cross-cultural studies (Henrich et al. 2010). Buried within this variance, however, are contrasting patterns: farmers in downstream *subaks* are less generous overall, while the most generous farmers of all are those in the two upstream *subaks* experiencing water shortages.[1]

1. This is consistent with the results of a recent study by Lamba and Mace: "That behavioral variation is at least partly contingent on environmental differences between populations questions the existence of stable norms of cooperation" (Lamba and Mace 2011:14426).

To explain these differences, size does not appear to matter: the two small downstream *subaks* resemble the large downstream *subaks* more closely than the small upstream *subaks*. Differences in genetic relatedness between the two groups are too small to affect cooperation directly (e.g., kin selection), and they do not suggest the exclusion of outsiders. Instead, they are consistent with the view expressed by several upstream farmers, that their *subaks* benefit from generations of shared history.

In ecology, the discovery of alternate stable states led to a shift from the investigation of equilibrium or near-equilibrium states to the study of stability boundaries for different regimes (Folke 2006). Here we have extended this approach to a tightly coupled social-ecological system, revealing a clear separation between two regimes, significant at four sigma. The more successful upstream *subaks* flourish in a small but deep basin of attraction. Confident in their collective ability to meet any challenge, they are exceptionally public-spirited. Their neighbors downstream cluster around their own attractor, revealing that muddling through can also be a steady state, with different dynamical relationships among state variables than in the upstream group.

But while this result confirms the ethnographic intuition of the anthropologist and some upstream farmers, it raises a new question about the meaning of the concept of regimes in an ethnographic context. Regime shifts in ecosystems are hard to miss, since they produce visible changes in the biotic community. Moreover, the dynamic behavior of ecosystems—their inner workings—are relatively clear-cut, compared to SES like Balinese *subaks*. Analytically, the key difference between the ecological view of regime shifts, and their meaning in the context of this study, is captured in figure 4. In ecology, the focus is on reversible changes in ecosystems that can be tracked using time-series data. But time is absent from figure 4: we would need to be extremely lucky to catch a *subak* in the midst of a regime shift, and it is possible that such transitions are rare. Instead, our interest is in the dynamic relationships that characterize each regime and in what can be inferred about the triggers for transitions between them. Each ellipse defines a basin of attraction within which the correlations between variables are nearly linear. In other words, variables like class or caste have similar effects among all four of the upper *subaks* and different, stronger effects among the four lower *subaks*. Each of the two attractors is an island of low-dimensional order within a higher dimensional manifold. Situating them within this space not only clarifies the differences between regimes; it enables us to calculate a hypothesis about the most probable transition between them. Thus, we need not wait for one of the *subaks* to embark on such a transition; the hypothesis can also be tested simply by gathering comparable data about more *subaks*.

To sum up, snapshots of the state of a handful of *subaks* based on simple survey data and a game yielded compelling statistical evidence for the existence of alternate regimes or steady states. Within each regime, conventional statistical methods explain most of the variance. But to discover the presence of alternate regimes, it was necessary to investigate the higher dimensional manifold in which their presence can be detected. This approach not only clarified the existence of two regimes with different dynamics; it also generated a hypothesis for the drivers of transitions between them. Thus, the empirical results from Bali are consistent with the mathematical argument with which we began: multiple attractors may be common in coupled SES, but if we are only looking for a single equilibrium, evidence of alternate steady states will be mistaken for noise.

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References Cited

Attayde, J. L., E. H. Van Nes, A. I. L. Araujo, G. Corso, and M. Scheffer. 2010. Omnivory by planktivores stabilizes plankton dynamics, but may either promote or reduce algal biomass. *Ecosystems* 13:410–420.

Barnosky, Anthony D., Elizabeth A. Hadly, Jordi Bascompte, Eric L. Berlow, James H. Brown, Mikael Fortelius, Wayne M. Getz et al. 2012. Approaching a state shift in Earth's biosphere. *Nature* 486:53–58.

Biggs, Reinette, Stephen R. Carpenter, and William A. Brock. 2009. Turning back from the brink: detecting an impending regime shift in time to avert it. *Proceedings of the National Academy of Sciences USA* 106:826–831.

Carpenter, S. R., J. J. Cole, M. L. Pace, R. Batt, W. A. Brock, T. Cline, J. Coloso et al. 2011. Early warnings of regime shifts: a whole-ecosystem experiment. *Science* 332:1079–1082.

Dearing, J., X. Yang, X. Dong, E. Zhang, X. Chen, P. Langdon, K. Zhang, W. Zhang, and T. Dawson. 2012. Extending the timescale and range of ecosystem services through paleoenvironmental analyses, exemplified in the lower Yangtze Basin. *Proceedings of the National Academy of Sciences USA* 109(18):E1111–E1120.

Folke, C. 2006. Resilience: the emergence of a perspective for social-ecological systems analysis. *Global Environmental Change* 16:253–267.

Goris, R. 1954. *Prasasti Bali: inscripties voor Anak Wungçu*, vols. 1–2. Bandung: C. V. Masa Baru.

Gutierrez, N., R. Hilborn, and O. Defeo. 2011. Leadership, social capital and incentives promote successful fisheries. *Nature* 470:386–389.

Henrich, Joseph, Jean Ensminger, Richard McElreath, Abigail Barr, Clark Barrett, Alexander Bolyanatz, Juan Camilo Cardenas et al. 2010. Markets, religion, community size and the evolution of fairness and punishment. *Science* 327:1480–1484.

Holling, C. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4:1–23.

Karafet, T. M., J. S. Lansing, A. J. Redd, S. Reznikova, J. C. Watkins, S. P. K. Surata, W. A. Arthawiguna et al. 2005. Balinese Y-chromosome perspective on the peopling of Indonesia: genetic contributions from pre-Neolithic hunter-gatherers, Austronesian farmers, and Indian traders. *Human Biology* 77:93–114.

Lamba, S., and R. Mace. 2011. Demography and ecology drive variation in cooperation across human populations. *Proceedings of the National Academy of Sciences USA* 108(35):14426–14430.

Lansing, J. 2006. *Perfect order: recognizing complexity in Bali.* Princeton, NJ: Princeton University Press.

———. 2007 (1991). *Priests and programmers: technologies of power in the engineered landscape of Bali.* Princeton, NJ: Princeton University Press.

Lansing, J., M. Cox, S. Downey, M. Jannsen, and J. Schoenfelder. 2009. A robust budding model of Balinese water temple networks. *World Archaeology* 41(1):112–133.

Lansing, J., T. Karafet, J. Schoenfelder, and M. Hammer. 2008. A DNA signature for the expansion of irrigation in Bali? In *Past human migrations in East Asia and Taiwan: matching archaeology, linguistics and genetics.* A. Sanchez-Mazas, R. Blench, M. Ross, I. Peiros, and M. Lin, eds. Pp. 376–394. London: Routledge.

Liu, Jianguo, Thomas Dietz, Stephen R. Carpenter, Marina Alberti, Carl Folke, Emilio Moran, Alice N. Pell et al. 2007. Complexity of coupled human and natural systems. *Science* 317:1513–1516.

Scheffer, Marten, Jordi Bascompte, William A. Brock, Victor Brovkin, Stephen R. Carpenter, Vasilis Dakos, Hermann Held, Egbert H. van Nes, Max Rietkerk, and George Sugihara. 2009. Early signs of critical transitions. *Nature* 461:53–59.

Schulte, Nordholt H. 1996. *The spell of power: a history of Balinese politics, 1650–1940.* Leiden: KITLV.

White, R. 1985. Historiographical essay, American environmental history: the development of a new field. *Pacific Historical Review* 54:335.