Averting Evolutionary Suicide from the Tragedy of the Commons

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ABSTRACT

In a tragedy of the commons, individual competition over a resource can reduce the resource itself, and thus reduce the fitness of the whole group. An extreme example is evolutionary suicide, which is predicted to occur when the selfish interests of free-riders and cheaters overwhelm cooperative behaviors, and the social good on which they depend ceases to exist. Case studies cite many different and seemingly interacting factors for success. Here we propose an equation-based theoretical model to predict changes in this balance, which determine whether the tragedy of the commons is observed in a particular scenario. Using survey data from 20 Balinese subaks, we explore the explanatory power of two theoretical traditions that are currently used to analyze commons management institutions, revealing multiple regimes with correlated responses to environmental threats. To explore case studies from a comparative perspective requires both theory and methods that can account for differences between regimes and explore transitions between them.

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Neoclassical economics enables us to predict how changes in prices affect market equilibria. But we have no comparable theory for common pool resources, which by definition lack prices. The utilization of these resources requires restraint on their exploitation by selfish actors, or the resource will cease to exist. N-person cooperation games (Santos et al., 2008) provide a framework to define this problem but do not explain why the balance between selfish and prosocial behaviors changes in particular scenarios. This problem is also at the forefront of research on the tragedy of the commons in evolutionary biology. Here we propose an equation based theoretical model to predict changes in this balance, which determine whether the tragedy of the commons is observed in a particular scenario. We highlight the potential significance of multiple equilibria because it bears on the explanatory power of the two theoretical traditions that are currently used to analyze commons management institutions, both of which require an assumption of equilibrium. Neoclassical economic analysis, including game theory, is based on the analysis of utility functions for individuals or firms, which yield equilibrium solutions, though multiple equilibria are possible (Crepin and Lindahl, 2008; Kossioris et al., 2008). A second approach developed by Elinor Ostrom (Ostrom, 1990) and colleagues analyzes the salience of the rules used to govern institutions engaged in the cooperative management of common property. The first approach assumes uniformity of agents, and the second approach assumes that the same rules will produce identical outcomes. If either assumption is violated, there may be more than one equilibrium solution, reducing the power of analyses that assume uniformity. Case studies cite many different and seemingly interacting factors for success, as Agrawal noted in 2002, and consequently "arrived at no consistent theory to explain viable and successful commons management", a problem that persists. (Agrawal, 2002; Rose, 2020)

It is predictable that multiple equilibria (Lade et al., 2013; Sugiarto et al., 2015) are likely to arise naturally in the management of the commons, because the incentives for collective action depend on both social relations (Chung et al., 2013) within the group and the efficacy of governance institutions, as well as the costs and benefits of the common resources. Adaptation is ongoing on both levels: sustaining effective collective action, and the tug-of-war between selfish exploitation, free – riding and active cooperation among the members. The resulting processes of ongoing co-adaptation to one another and challenges to the group can produce divergent outcomes. We observe this in the twenty Balinese communities in our study, which share identical goals – the effective management of irrigated rice terraces – and identical governance rules,

designed to sustain high levels of consensual cooperation. A sample survey of about 25 farmers in each of the 20 communities showed that they vary in their success in meeting these goals, as well as their internal dynamics. Analysis of the survey results showed that the 20 subaks fall into three distinct, sharply contrasting attractors[1] with correlated responses.

In a tragedy of the commons, individual competition over a resource can reduce the resource itself, and thus reduce the fitness of the whole group. Evolutionary biology offers clear illustrations of this phenomenon. An extreme example is evolutionary suicide, which is predicted to occur when the selfish interests of free-riders and cheaters overwhelm cooperative behaviors, and the social good on which they depend ceases to exist. This occurs, for example, in Cape honey bees, when workers cease to help the colony and instead invest in their own selfish reproduction, leading to very few individuals becoming workers, and in turn, colony collapse. (Martin et al., 2002) Biologists distinguish between "collapsing" tragedies in which the entire resource vanishes, which can lead to the extinction of the group, and "component" tragedies[2] resulting in a lower average fitness for the group as a result of selfish competition, although the group still persists on the resource in question. There is thus a continuum between component and collapsing tragedies, which prompts the question "why component tragedies do not always become collapsing tragedies, or why individuals in some cases cooperate so diligently that even component tragedies are absent?" (Rankin et al., 2007).

In the simplest case, all that is required is restraint in the exploitation of the shared resource. But in the cases to be considered here, more is required: self-interested competition must give way to collective action to sustain the shared resource, as is evident from ethnographic and historical studies of the cooperative management of Balinese irrigation (Lansing and de Vet, 2012). This minimally requires an effective system of governance, which determines the steering capacity of the group. We suggest that it varies in response to threats to the benefits that members accrue from the group's shared resource. Threats to vulnerable resources that produce significant benefits can motivate higher investments in the steering capacity that sustains them, damping down internal competition or free-riding.

We tested this hypothesis with a sample survey of farmers in each of the 20 Balinese rice-growing communities in our study. These communities are not villages; rather they are specialized institutions called subak, whose members collectively manage their irrigation systems. Subaks have existed in Bali since the 11th century (*Figure 1*). They provide a good test for the steering capacity hypothesis for several

Figure 1 A subak meeting in a Balinese village. Although the Balinese language includes registers (high and low) connected with the relative caste status of the speaker and hearer, during these meetings the registers are set aside and all participants are strongly encouraged to speak in the same register, signalling their equal status in the subak. See text for analysis of the consequences for governance.

reasons: they are independent, self-organizing and self-governing institutions that tend to persist for generations. Prior research shows that they are vulnerable to both component and collapsing tragedies of the commons. (Lansing, 2006) Our analysis proceeded in three steps. First, we undertook a survey of the farmer's views on pro-social behavior in their subak, the effectiveness of its governance institutions, and environmental conditions. Second, we drew from the results to formulate and test an equation that predicts changes in steering capacity in response to threats to the continued benefits from the shared resources managed by the subak. Third, we analyzed variation at the subak level that bears on the likelihood of movement towards or away from component tragedies in response to changes in steering capacity.

DISCOVERING ATTRACTORS USING SURVEY DATA

Subaks are traditional, community-scale institutions that manage irrigation flows into rice paddies. The ancient polycentric governance of subaks emerged over hundreds of years and has been extensively studied (Lansing and de Vet, 2012; Lansing et al., 2017). The subak system requires farmers to share limited water and suppress rice pests by coordinating their crop planting schedules, and managing local networks of irrigation canals. This is achieved through regular subak meetings guiding collective action which, when successful, increase crop yields of individual farmers and the subak as a whole (Lansing et al., 2017). Coordination is required for stable crop yields, and in the long run cooperation by farmers is the norm, consistent with a model of co-adaptation that predicts the emergence of Pareto optimality when local groups of subaks cooperate. (Lansing, 2006) But cooperation sometimes falters, usually for brief periods but occasionally permanently. To characterise the functioning of the subaks as social-ecological systems from a comparative perspective, we designed a comprehensive 35-question survey covering environmental, social and institutional variables.[3]

We enrolled approximately 25 traditional farmers from each of 20 geographically dispersed and diverse subaks in the survey. In the first stage of data analysis, we removed relatively unimportant descriptors by means of higher-order clustering (Sugiarto et al., 2017), and analyzed the remaining 19 descriptors (*Table 1*) using principal component analysis (Legendre and Legendre, 1998). We observe three groups of closely correlated descriptors,

DESCRIPTOR #	DESCRIPTOR	DESCRIPTOR #	DESCRIPTOR
1	Own farmland	19	Pest damage in subak
2	Sharecrop land	20	Pest damage myself
3	Inherited a farm	21	Thefts of water
4	Purchase	22	Conflicts among members
5	Sold a farm	23	Choice of subak head
6	Income	24	Fines
7	Harvest	25	Crop schedule followed
8	Satisfaction with harvest	26	Plan work
9	Origin	27	Written rules followed
10	Condition of canals	28	Fines frequency
11	Condition of fields	29	Condition of subak
12	Synchronize	30	Decisions of subak accepted
13	Attendance at meetings	31	Technical problems
14	Participation in maintenance	32	Social problems
15	Attendance at ritual	33	Caste problems
16	Accept subak decisions	34	Class problems
17	Water shortages in subak	35	Resilience
18	Water shortages myself		

Table 1 Survey topics used in this study. The 19 questions used in the reduced list for analysis are highlighted. The use of higher order clustering to reduce the number of descriptors from 35 to 19 is explained in SI B.
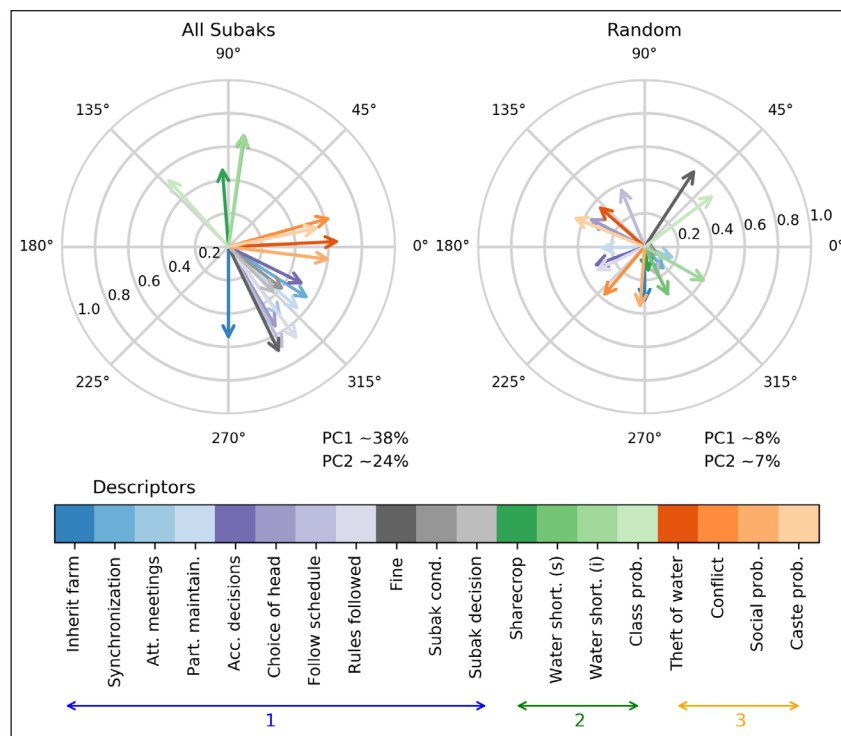

Figure 2 Comparison of PCA biplots of survey data from all 20 subaks, and from randomized samples as control. The randomized samples are obtained by shuffling the responses of all the farmers to each question independently, re-running the PCA, and calculating the biplot (see the Matlab codes section for a sample code used to plot the biplot). Each descriptor is assigned a unique color. The length of the arrow for each descriptor indicates its magnitude (contribution to the PCA). Arrows that are closer together are more correlated. Note that the direction of each arrow is relative to that of the descriptor "inherit farm" which is a fixed reference at 270° for both biplots. Blues, purples and greys are cooperative descriptors (1); greens are defective descriptors (2); and oranges are social disharmony descriptors (3).

which we term groups 1, 2, and 3 (***Figure 2***). Group 1 contains correlated descriptors which depend directly or indirectly on the cooperativity of the farmers. Group 2 is anti-correlated with group 1 and corresponds to defection. The relevant descriptors are mainly associated with problems such as limited water availability at both the individual and subak level. The survey questions in Group 2 also include the proportion of owners versus sharecroppers, and whether class differences (likely to be correlated with land ownership) affect non-cooperative behavior. Group 3 is related to breakdowns in pro-social behavior and rule following, and is observed to be uncorrelated with groups 1 and 2. It has descriptors such as conflicts among members, class and caste antagonisms and frequency of water theft.

The Principal Component Analysis distribution at the farmer level showed weak correlations. But survey results at the subak level reveal clusters of subaks with similar principal components (***Figure 3***). Projecting the mean responses of the 19 descriptors for each subak into an embedding space of two dimensions, accounting for 62% of variance (PC1 = 38% and PC2 = 24%), subaks are dispersed in three different-sized clusters with significant differences in their responses to survey questions (see SI). A plot in an embedding space of three dimensions (with PC3 accounting for 9.6% of variance) confirms clustering behaviour, because more of the variance is explained under the assumption that the subaks fall into three distinct clusters. The alternative hypothesis, a single regime with

some subaks as outliers, dramatically reduces the power of the PCA. Using information theory, as will be explained below, we characterize these clusters as subak-level regimes and analyze the differences between them. To explain these differences between subaks, we created a model (***Table 2***).

A MODEL OF STEERING CAPACITY

For subaks to sustain their steering capacity, self-interested competition must give way to strategic collective action. We predict that pro-social behavior will be sustained and obstacles to effective collective decision-making (steering capacity) will be suppressed as threats to the resources shared by the group increase. The components of the model are as follows:

1. SC, Steering capacity
2. T, Threats: the magnitude and proximity of perceived threats to the shared resource
3. D, Dominance: departures from mandated pro-social behavior
4. B, Breakdowns: breakdowns in rule-following by members

The equation for the model is:
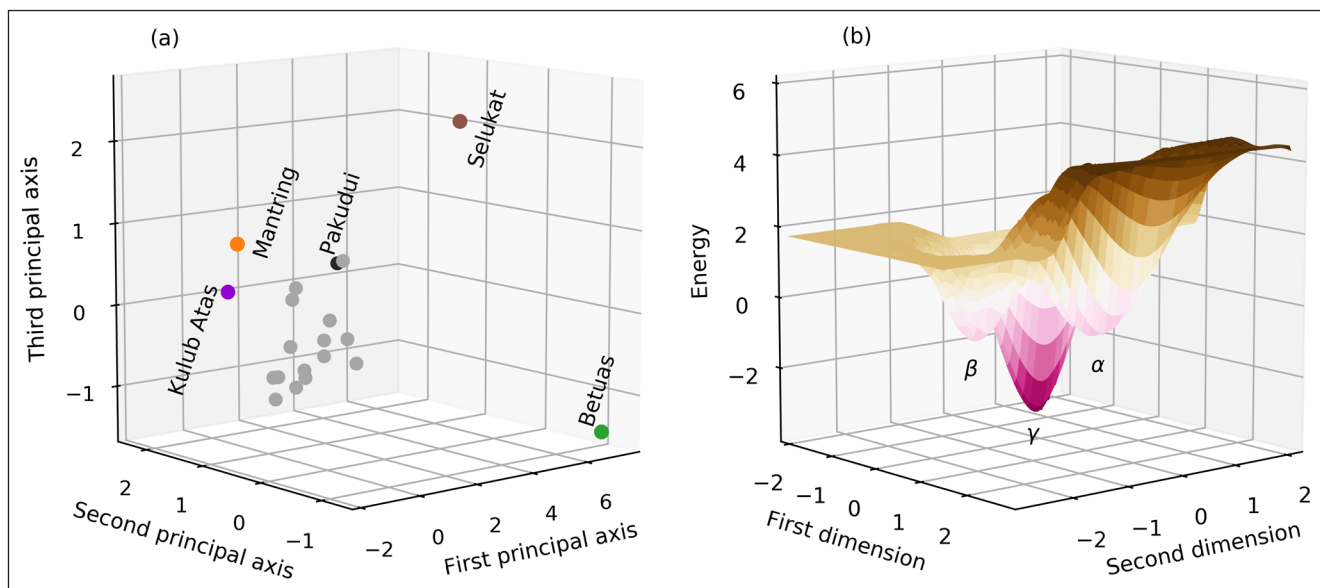
$$SC = f(T, -D, -B)$$

(1)

Figure 3 Analysis of the survey results shows that survey responses cluster at the subak level, indicating that certain combinations of attitudes are common. **(a)** PCA at the level of subaks rather than individual farmers shows one large cluster (grey) and 5 subaks that are outliers. 19 descriptors account for most of the variance (PC1 = 38%, PC2 = 24%, PC3 = 9.6%.). **(b)** Energy landscape analysis based on Fisher Information at the subak scale shows three attractors corresponding to the PCA clusters. The more cohesive the descriptors within a cluster, the denser the state and the greater the depth.

SUBAK NUMBER #	NAME	VARIABLES		
		B	D	T
1	Tampuagan Hilir	0	1	25
2	Mantring	13	7	42
3	Tampuagan Hulu	1	0	9
4	Kebon	0	0	64
5	Calo	0	0	52
6	Cebok	0	0	51
7	Bayad	0	0	60
8	Timbul	0	0	47
9	Kedisan kaja	0	0	38
10	Kedisan Kelod	0	0	38
11	Jasan	0	1	32
12	Selukat	0	14	10
13	Sebatu	0	0	52
14	Betuas	71	16	24
15	Pakudui	0	8	19
16	Aban	0	1	37
17	Teba	1	1	45
18	Dukuh	23	1	28
19	Tegan	4	2	64
20	Kulub Atas	4	3	90

Table 2 Parameter values for each subak for the Steering Capacity equation. See Section F of SI for variables.

TESTS OF THE MODEL

As predicted by Eq. 1 and shown in *Figures 4–6*, when threats to the shared resources managed by subaks increase, obstacles to effective collective decision-making (steering capacity) are suppressed. Within each attractor, the responses of the farmers are closely correlated. The largest cluster contains 16 subaks. We label it Attractor γ. It is tightly grouped and shows the greatest uniformity in variables related to cooperation, including synchronized cropping, participation in subak meetings and maintenance of the irrigation works and subak rituals. Less cooperative subaks are distributed in Attractor α (subaks Betuas and Selukat) and Attractor β (Mantring and Kulub Atas) (*Figure 7*). The patterns of correlations are nearly linear in each attractor, but different between attractors (*Figure 8*).

To evaluate the strength of the attractors for the principal components of the 3 clusters of subaks we use Fisher Information (FI), which unlike PCA does not assume that correlations are linear. FI measures the amount of information that an observable random variable X carries about an unknown parameter of a distribution that models X. It describes the probability that we will observe a given sample X, given a known value of θ (see SI). The combination of PCA and Fisher Information produces a Fisher Information landscape, which gives a visual perspective of the regimes of stability of the dynamical system of interest. The strength of each attractor for a given configuration of PCs in clusters of subaks can be calculated by their densities on a Fisher information landscape, which can be represented by depth: the more cohesive and influential the descriptors, the denser the state and the greater the depth (*Figure 3b*). This facilitates comparisons between attractors. We find that subaks form distinct clusters according to their survey responses, indicating that combinations of attitudes vary systematically between attractors and are thus meaningful differences. Attractor α has the greatest variation in descriptors that are either correlated or anti-correlated with cooperativity, such as water shortages and fines. These subaks, Betuas and Selukat, are located near the sea, near the terminus of their irrigation systems, but nonetheless have abundant water thanks to eleven natural springs. Indeed these two subaks scored highest on satisfaction with water availability. But in 2002 it became known that a coastal highway would go through their land, and speculators began to buy up subak land in anticipation of the construction of the highway. After the road was completed, many farmers leased their own land back from the speculators, and so became sharecroppers. The highway bisects both subaks, and the heads of both subaks said that the subaks are now in danger of collapse. In the survey, farmers described the condition of their subaks as
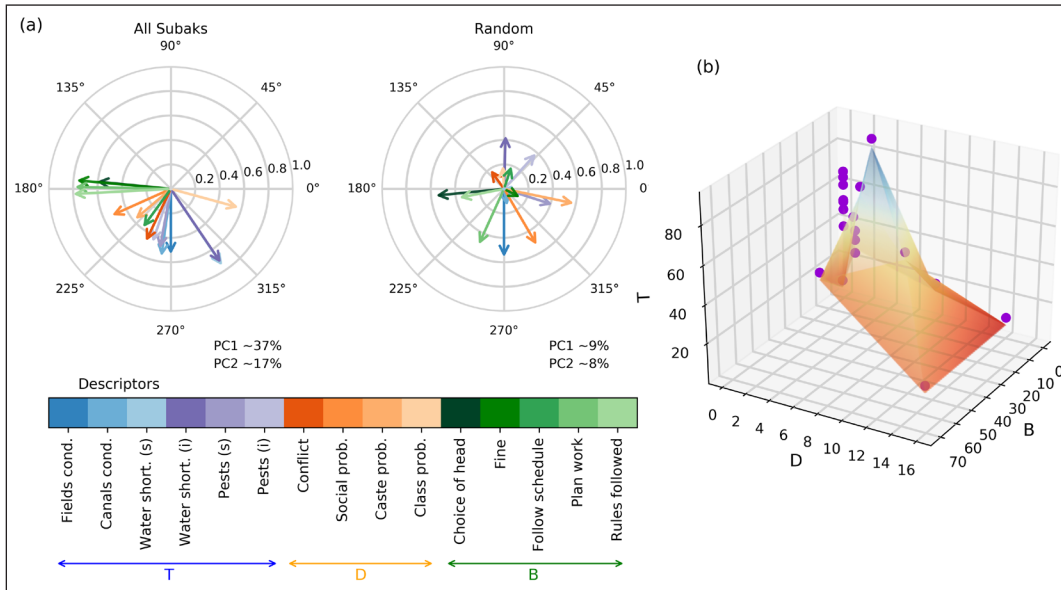
Figure 4 Relationship of perceived environmental threats *T* to the suppression of social dominance behavior *D* and breakdowns in consensus-based collective decision-making *B* based on surveys of 496 farmers in 20 Balinese subaks. These variables are a subset of the full set in Figure 1 and have different colors. The greater the threat *T* (based on the mean of 7 variables), the fewer breakdowns in collective management by the subak *B* (4 variables), and the less dominance-related behavior *D* (4 variables). Left: Principal Components analysis of responses to the survey questions that define *T, B* and *D*. These are a subset of the variables (see Figure 1). The length of each vector arrow is proportional to the statistical significance of a survey question, and its direction is proportional to its correlation with other survey questions. Right: Each dot represents aggregate survey results for a single subak. At low levels of threat (*T*), both *B* and *D* are present in some subaks. As *T* increases, *B* and *D* rapidly decline. We interpret this to mean that as perceived environmental threats to the group increase, obstacles to effective collective decision making (steering capacity) are suppressed.
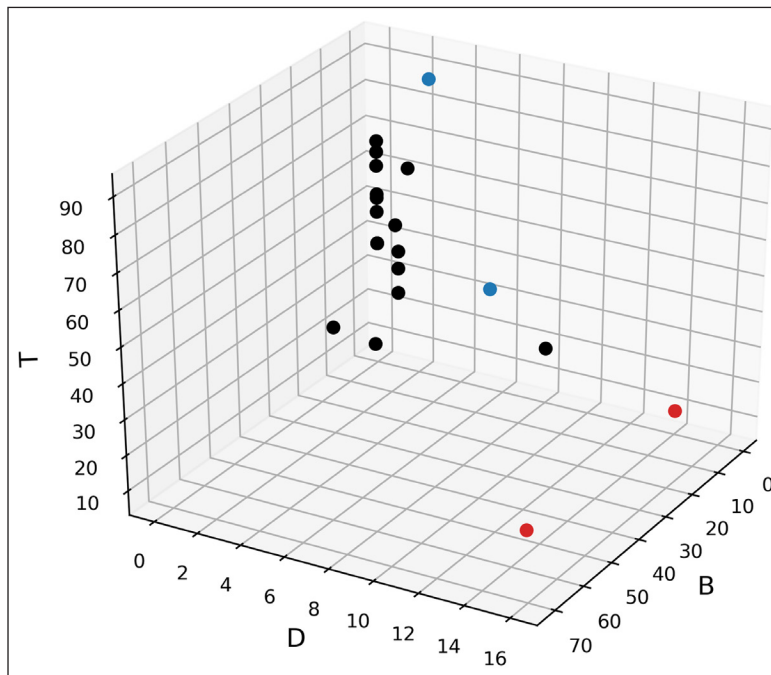

Figure 5 Steering capacity model with colours for the three different attractors. Attractor is red (subaks Betuas and Selukat), Attractor is blue (subaks Kulub Atas and Mantring); the remaining 16 subaks in Attractor are black. Note that the observables *T, D* and *B* are to be treated as independent variables in *SC* = *f*(*T,–D,–B*), which expresses the generic feature of steering capacity as a quantity that increases with perceived environmental threat, and decreases under social dominance behaviour as well as breakdown in consensus based collective decision-making. Thus these figures should not be interpreted as a relationship between *T, D* and *B*. Instead the figure shows that subaks with high *T*, low *D*, and low *B* (black dots) have high steering capacity; and those with relatively low T and relatively high *D* and *B* (red and blue dots) have a relatively lower steering capacity.

poor in Betuas (mean response 2.85) and fair in Selukat (3.29). For comparison, the mean response for "condition of my subak" for all subaks was 3.82. Threats to these subaks are extrinsic, beyond their control, not the results of internal conflicts or mismanagement. These two subaks have the worst Dominance scores, but only Betuas has a very high Breakdown score, indicating that the steering capacity is very low, and the subak has entered a collapsing tragedy of the commons. In both of these subaks, high Dominance scores signal erosion of prosocial behavior within the subak.

Subaks Mantring and Kulub Atas (Attractor β) cope with different problems. Kulub Atas has the highest Threat scores and moderate Breakdowns. We revisited this subak and confirmed the survey results indicating that the main irrigation canal of Kulub Atas needs repair, water shortages are frequent, and the head of the subak is unpopular. Surprisingly, the overall condition of Kulub Atas was rated 3.64 by the farmers, consistent with continuing faith in the steering capacity of the subak despite severe environmental problems (high Threat), and moderate B and D. Mantring had the lowest harvest of the 20 subaks, and scores were low for satisfaction with harvests, social problems, frequent water theft, irrigation canals in poor repair, and poorly synchronized irrigation schedules. The score for Threat was very high, yet the farmers rated the overall condition of their subak at 3.70 (slightly below average). In tandem with slightly elevated Dominance scores, the model predicts that, like Kulub Atas, the farmers in Mantring are experiencing high T and responding by attempting to sustain the steering capacity of their subak.

With regard to Attractor γ, we note that while most of the 16 subaks show impressive homogeneity (e.g. Kedisan Kaja and Kebon), some others, still deep within Attractor γ, include some variability, such as #18 Dukuh and #19 Tegan (*Figure 6*). Probing the survey results for these two subaks, we observe that Dukuh is plagued by a high level of Breakdown issues while Tegan is more adversely affected by poor environmental conditions in comparison to the other cooperative subaks. Both of them also face the social problem of more frequent water thefts. Tellingly, farmers in these two subaks describe the role of democracy in the governance of their subak as a "veneer" rather than an actuality, at higher rates than the other cooperative subaks.

A further test of the model is provided by another subak that lies deep in the cooperative regime (γ). Analysis of the Fisher Information (see SI) as well as its location on the energy landscape suggests that this subak, #15 Pakudui, is more resilient (has greater steering capacity) than the raw questionnaire data suggests. This subak is not plagued by environmental threats T, but rather by D, dominance. The overall pattern of responses situates Pakudui in the cooperative regime (*Figure 6*). But the response to Question
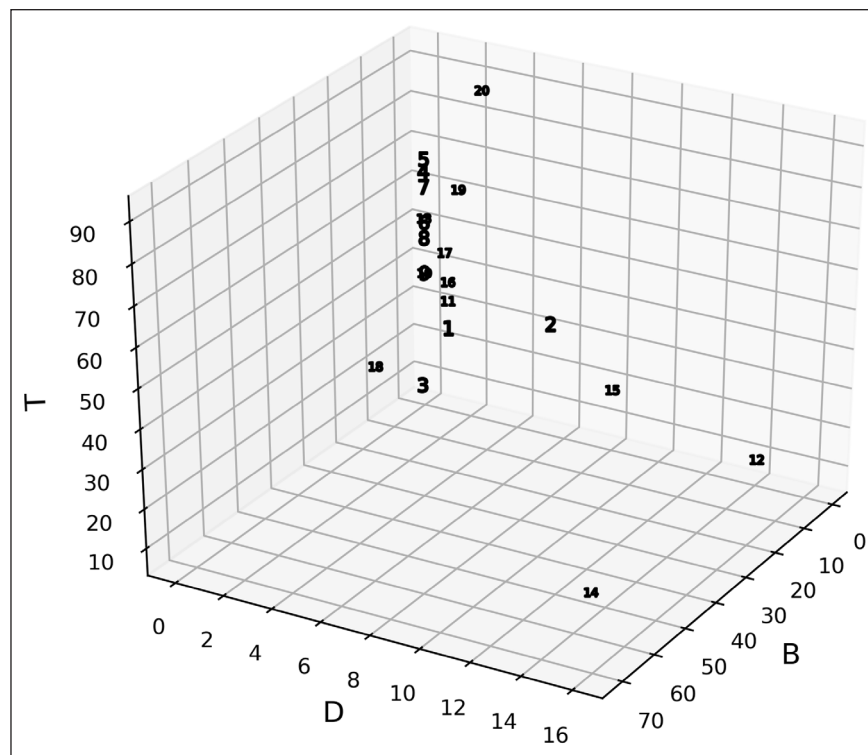

Figure 6 Steering capacity model with numbered subaks in the attractors. Attractor includes 14 Betuas and 12 Selukat; Attractor includes 20 Kulub Atas and 2 Mantring. 15 Pakudu is an interesting outlier in Attractor , see text. See table 2 for parameter values based on the 19 variables used for analysis.
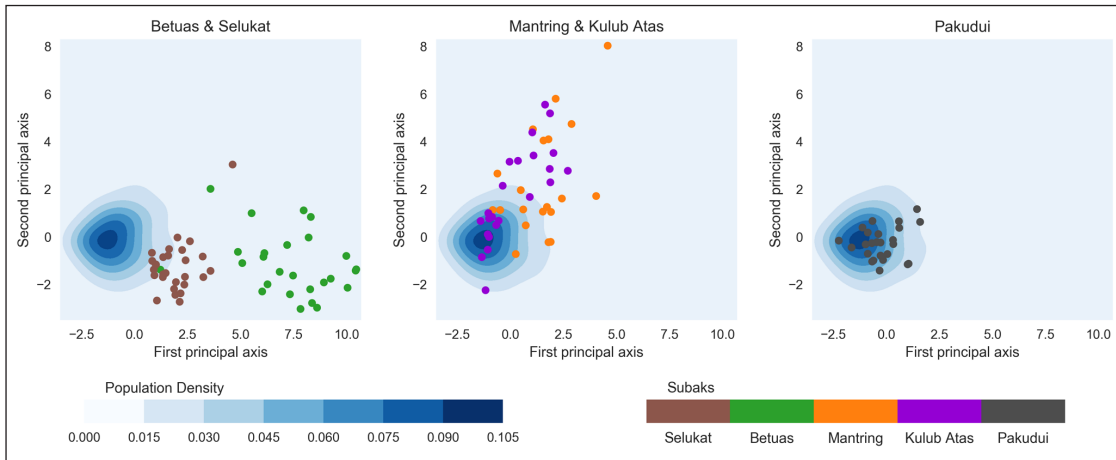
Figure 7 Fisher Information landscape showing clustering of survey responses at the subak level. Here, we project survey answers of the 493 farmers onto the first two principal components, and calculate the density of the population in the principal component space. The density of a state is defined as the number of subaks per state (See Methods and SI). Most of the farmers lie at the centre of the blue rings, which enclose the survey responses from subaks in Attractor γ, which we interpret as exhibiting high steering capacity. Colored dots show the responses of individual farmers in subaks in Attractor α and Attractor β, which are both more divergent and less cohesive than Attractor γ, with lower Fisher Information. As noted in the text, the steering capacity of #15 Pakudui, which lies within Attractor γ, is being tested by social conflicts extrinsic to the subak itself.
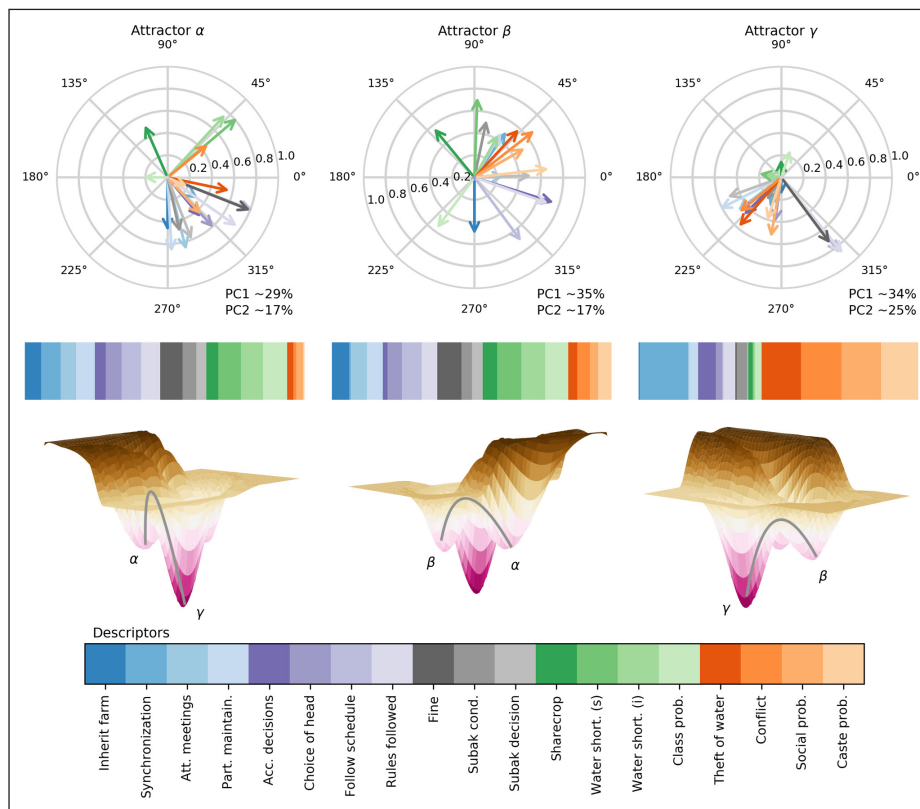

Figure 8 Transition paths between the regimes calculated from the energy landscape analysis. Equation 1 predicts different solutions for each regime, each of them nearly linear within that regime, because the correlations among variables are different for each regime. The top panel shows the biplots for the three regimes. The direction of each arrow of the biplots is relative to that of the descriptor "inherit farm" which is a fixed reference at 270°. Attractor α includes Subaks Betuas and Selukat; Attractor β consists of Mantring and Kulub Atas; all other subaks are in Attractor γ. Below this panel, the colored band shows which descriptors dominate along hypothetical transition paths between regimes (attractors). Environmental variables (in green) and fines dominate the path from α to γ, but have little influence on the path from β to γ, which is dominated by social conflicts (in red). Thus a reduction in environmental problems would lead a transition from α to γ, while reduction in social conflicts would lead from β to γ. The third panel shows the energy landscape and these transition paths. Beneath it the colored band shows all 19 descriptors.

33 (caste problems) did not fit this pattern. This question asked "In your opinion, is there a connection between the capability of the subak and caste conflicts within the subak?" Farmers had three choices: Frequently (scored as 1), sometimes (scored as 2), and seldom (scored as 3). The mean response for all subaks was 2.94, but for Pakudui it was 1.88. This anomaly led us to revisit the subak to inquire about caste. We learned that there has been a long-standing dispute between two groups in the village, numbering 60 and 15 households, about their caste prerogatives. The origins of the conflict go back to a dispute that began in the 1960's about the management of income from the sale of rice belonging to a village temple. One group claimed that they were exempt from the responsibility to contribute to the annual ritual cycle at the temple, because they should be credited with the income from the temple's ricelands. This dispute quietly simmered for decades, but heated up the year before our survey when one group refused to allow a member of the other group to be buried in the cemetery for two days until police intervened.

What's interesting about this result is that this severe social conflict apparently did not cause the subak to become dysfunctional, even though members of the two groups barely speak to one another. Responses to the other survey questions were clustered within the cooperative regime (*Figure 7*), and the Fisher Information fell within the middle range. As predicted by the model, Pakudui retained its steering capacity: threats were moderate, social tensions within the subak were actively suppressed and breakdowns in the functioning of the subak averted, thus keeping the flow of benefits from the subak intact.

Overall, we interpret these results in terms of movement along a continuum from well-functioning subaks with high steering capacity to component and in the case of Betuas, collapsing tragedies of the commons. Significantly, the PCA biplot analysis on variables that comprise T, D and B shows that Breakdown is uncorrelated with Threat in Attractor γ. This implies that institutional governance is functioning independently from threats to the shared resource. In Attractor α, farmers fail to provide correlated responses to questions related to threats. Moreover, they possess uncorrelated perceptions of the various aspects of institutional governance. Environmental threats are low for both subaks, but cooperation has broken down because for extrinsic reasons the subaks are no longer viable. Farmers in these subaks find themselves deep in a component tragedy of the commons. In contrast, for subaks in Attractor β, Threat anti-correlates with Breakdown: institutional governance functions only in response to threats. High Threat is associated with low dominance while low Threat correlates with high Dominance, as predicted by equation (1). Finally, Pakudui is in Attractor γ but borders on Attractor

α. It experiences social conflicts (D) but so far continues to function well, with high steering capacity. The equation predicts that higher threats would push it away from Attractor α, deeper into Attractor γ.

DISCUSSION

Balinese farmers and subaks actively cooperate to minimize losses from pests and water shortages by fine-tuning their irrigation schedules. In prior research we modeled this process and found that by balancing optimization for pest control versus water sharing, subaks tend to evolve toward an optimal state in which total harvests are maximized and the system approaches Pareto optimality. Multispectral image analysis of collective crop management by the subaks – observable in Google Earth – closely matches the predictions of the model (Lansing et al., 2017). Counterintuitively, the threat of pests in the fields actually promotes cooperation because of the need to reduce their numbers by synchronizing harvests and temporarily removing their preferred habitat. This result- an adaptive process triggering a phase transition – has now been generalized. (Gandica et al., 2021)

But this model of adaptive self-organization does not address the question of how cooperation is actually achieved or sustained; instead it shows how the observed spatial patterning of cooperation can emerge if farmers seek to optimize their harvests. In this paper we have turned our attention to the social dynamics. By comparing the Fisher information in the three attractors, we show that the most stable attractor is ongoing pro-social behaviour and rule-following, apparently sustained by the ever-present threat of harvest losses if collective management begins to falter. This provides an explanation for the avoidance of evolutionary suicide and the persistence of the subak system since its invention a thousand years ago, as well as the occasional collapses. The use of Fisher Information to characterize the patterning of survey responses within the regimes makes it possible to observe not only the key differences in their social dynamics, but also the depth and stability of the resulting patterns. Finally, the energy landscape analysis (*Figure 8*) facilitates visualization and analysis of probable transition paths towards or away from evolutionary suicide, suggesting possibilities for future comparative research.

To explore case studies from a comparative perspective requires both theory and methods that can account for differences between regimes. This opens the door to comparative quantitative analysis of the sustainability of the commons. In the twenty cases analyzed here, steering capacity varies in response to threats to the collective

benefits from common property, involving both suppression of dominance behavior and active commitment to rule-following and governance institutions. Our results support Ostrom's observation that social scientists "need to recognize that individual behavior is strongly affected by the context in which interactions take place rather than being simply a result of individual differences." But they also indicate that the relevant context can extend beyond institutional regularities (the focus of Ostrom's analysis) to the nonlinear dynamics of social and social-environmental interactions. We suggest that further progress in the analysis of case studies of coupled social-environmental systems, particularly those involving the collective management of common property, will benefit from adding a new layer of comparative analysis, relating the behaviour of individuals to the steering capacity of self-governing institutions, which requires an historical perspective. We return to this topic in the conclusion.

CONCLUSION: DISCOURSE AND STEERING CAPACITY

In the 1980's the question of the "steering capacity" of institutions played a central role in the theory of social evolution developed by Jürgen Habermas, who had emerged as the leading scholar of the Frankfurt School. One of Habermas' key insights was that "discourse" involves more than strategic communication or even rational argument. Instead it requires a venue in which the goal of communication is the objective assessment of truth claims by a group of individuals whose competence is acknowledged. In this way, discourse endows institutions with steering capacity. We suggest that this analysis is relevant to the functioning of subaks and other self-governing systems of commons management.

In his own writings, Habermas was interested in the initial expansion of the public sphere in eighteenth century Germany, France and Britain, in what would later become the first scientific societies: "However much the *Tischgesellschafter*" (cafés), salons and coffee houses may have differed in the size and composition of their publics, the style of their proceedings, the climate of their debates and their topical orientations, they all organized discussion among private people that tended to be ongoing; hence they had a number of institutional criteria in common. "First, they preserved a kind of social intercourse that disregarded status altogether... Second, discussion within such a public presupposed the problemization of areas that until then had not been questioned. Third...the issues discussed became "general" not merely in their significance, but in their accessibility..." (Habermas, 1989) Key elements were

the disregard of status and the expansion of domains of common concern.[4]

Something quite similar (in the form of an expansion of the public sphere) must have begun in eleventh century Bali, when the villagers who had begun to construct irrigation tunnels and canals began to call themselves subaks, and came to the attention of the court officials writing royal in scriptions.[5] To function effectively (and provide tax revenue to the royal treasuries), the farmers needed a venue for making collective decisions in which a consensus could reliably be achieved. Several of our survey questions addressed this point:

> Q27-31: "Concerning decisions or results from subak meetings, which of the following reflect real democracy and which are just a democratic veneer?" [Selection of subak head; fines; choice of cropping pattern; organization of collective work; reading and following the written rules of the subak]

The survey results showed that any doubts on this point were sufficient to move the subak out of the cooperative regime (γ). All subaks have formal rules for the conduct of meetings, which are usually articulated in written charters (*awig-awig*). An important and very widespread rule forbids members from speaking in meetings using caste-based language registers, because in ordinary speech these registers signify inequality. Instead all members should speak in the same respectful register. If anyone begins to speak in the informal register of Low Balinese, then everyone should follow suit, because that also signifies treating each other as equals. Habermas' analysis is relevant here: these rules do more than assert the presumption of equality within the subak. By so doing they avoid appeals to authority as the basis for decisions, and make it possible for proposals relevant to the collective interest to be articulated and objectively assessed. In short they exemplify Habermas' thesis that the institutionalization of discourse is a prerequisite for the emergence of steering capacity in a self-governing institution.

In what Habermas later came to call "strong communicative action" in "Some Further Clarifications of the Concept of Communicative Rationality" (1998b, chap. 7), speakers coordinate their action and pursuit of individual (or joint) goals on the basis of a shared understanding that the goals are inherently reasonable or worthwhile. The step from "strong communicative action" to "discourse" requires the further condition that the purpose of communication is the evaluation of validity claims. Thus discourse becomes a theory of argumentation, which Habermas calls the "reflective form" of communicative action. So are the subak meetings strong

communicative action or discourse? Put another way, what is actually required to sustain the steering capacity of a subak? The question may seem esoteric, but as we have seen, subaks are fragile institutions. As James Bohman and William Rehg observe, "What Habermas calls "theoretico-empirical" or "theoretical" discourse becomes necessary when beliefs lose their unproblematic status as the result of practical difficulties, or when novel circumstances pose questions about the natural world. Such cases call for an empirical inquiry in which truth claims about the world are submitted to critical testing." (Bohman and Rehg, 2014) This description seems closer to the actual practices of the subaks. While the topics discussed in subak meetings are often prosaic, challenges do arise.[6] When they do, the rules of discourse come to the fore, and the ability to craft well-reasoned arguments is valued and admired. (Hobart, 1975).

After centuries of expansion along Bali's rivers, today roughly 800 subaks survive on the island. Since 2010, when they managed approximately 86,000 hectares of rice paddies, between 1000 and 2000 hectares have gone out of production each year. Our analysis of survey data shows that the resilience of subaks largely depends on their social dynamics. Steering capacity emerges from and is sustained by active participation in the discourse of subak meetings. Leaders are usually chosen by unanimous consent, and

once the subak has made its choice, this honor is not easily refused, because "the voice of the subak is the voice of God." The voluntary rituals performed by the subaks are said to "strengthen the foundations" (*negteg linggih*) and are considered to be beneficial for the whole of the Balinese world.

METHODS
QUESTIONNAIRE SURVEY

We designed the questionnaire survey based on Lansing's expert knowledge of the Balinese subak system, asking 35 questions that capture a broad swathe of information about the condition of the subaks, the lives of farmers and their opinions about the functioning of their subaks. Since not all descriptors proved to be useful, we reduce the number of descriptors by removing those that are relatively insignificant using higher-order clustering (Sugiarto et al., 2017). The strategy is to discriminate the irrelevant descriptors from the more informative ones using a distance matrix. This led to 19 reduced descriptors as shown in *Table 1*. Projecting the mean responses of the 19 descriptors for each subak into an embedding space of three dimensions, subaks are dispersed in different-sized clusters (see SI). The loading matrix of the 19 descriptors is given in *Table 3*.

DESCRIPTOR #	DESCRIPTOR	COMPONENTS		
		1	2	3
3	Inherited a farm	−0.6758	0.4621	0.2448
12	Synchronize	−0.8662	−0.1861	−0.1163
13	Attendance at meetings	−0.8429	0.0664	0.0860
14	Participation in maintenance	−0.8938	−0.0684	0.0717
16	Accept subak decisions	−0.7376	−0.2356	0.2600
23	Choice of subak head	−0.8230	0.0847	0.0655
26	Plan work	−0.9670	0.1173	0.0815
27	Written rules followed	−1.0031	0.0031	0.0231
24	Fines	0.1244	0.0431	0.0317
29	Condition of subak	−0.6587	−0.0983	−0.0828
30	Decision of subak accepted	−0.6433	−0.0232	0.4136
2	Sharecrop land	0.6190	−0.3588	−0.2771
17	Water shortages in subak	0.7361	−0.6646	0.2997
18	Water shortages myself	0.7519	−0.6666	0.2749
34	Class problems	0.8679	0.0026	0.3283
21	Theft of water	−0.6333	−0.6276	0.0693
22	Conflicts among members	−0.4316	−0.6765	0.0407
32	Social problems	−0.7157	−0.4868	−0.2364
33	Caste problems	−0.4227	−0.5815	−0.2555

Table 3 Loading Matrix of the 19 descriptors for energy landscape analysis.

PRINCIPAL COMPONENTS ANALYSIS AND FISHER INFORMATION

Principal Components Analysis (PCA) can be combined with Fisher Information (FI) to gain insight into Attractor basins (Frank, 2012; Mayer et al., 2007). FI measures the amount of information that an observable random variable X carries about an unknown parameter θ of a distribution that models X. A high FI indicates that it is easy to deduce the true value of θ through sampling X. Conversely, it is difficult to determine the true value of θ when FI is low, and many samples of X are required. FI is routinely used by astronomers to forecast what can be learned from future observations, with the aim of testing theoretical models while they are still in the design phase (Machta et al., 2013). An advantage of FI is that it does not assume that correlations are linear. Instead it characterizes the probability distributions of each descriptor. The combination of PCA and Fisher Information produces a Fisher Information landscape, which gives a visual perspective on the regimes of stability of the dynamical system of interest.

The Fisher Information F is defined based on the conditional probability distribution $p(X|\theta)$ using the log-likelihood function $L(\theta | X) = \ln(p(X | \theta))$ as follows:

$$F(\theta) = \int_X \left(\frac{dL(\theta|X)}{d\theta} \right)^2 p(X|\theta) dX \qquad (2)$$

under the assumption of a continuous X.

Intuitively, this weights the probability of observations by the extent to which they constrain θ. A flat log-likelihood surface of θ with respect to X implies that an observation provides little information about θ, and the Fisher Information is low; conversely if the loglikelihood surface is sharply peaked then it is relatively easy to constrain θ through observations and the Fisher information is high. Having generated the PCA based on the reduced 19-question set of responses from all individuals, for each subak we:

1. Project all members of that subak onto a principal component axis
2. Fit three statistical distributions (Gaussian, Rayleigh or Pareto) to the distribution of individuals on that axis by maximum likelihood and calculate their sum of squared error (sse). The distribution with the lowest sum of squared error is accepted as the distribution that best describes the data.
3. Calculate the Fisher Information F(μ) of that distribution, where μ is the first statistical moment

This is performed for the first and second principal components. The sum of the Fisher Information of these two principal components then form the overall Fisher Information measure of the subak. After plotting this measure for each subak atop the PCA space, we use a Gaussian kernel density estimation (KDE) to interpolate between the points to constitute a Fisher Information surface (Fig. S7 in the supplementary information).

We use Fisher Information to examine the relationship between PCA which seeks linearly uncorrelated components that capture the greatest variance among all individuals in the survey and the population units in which these individuals exist. Specifically, we are seeking to characterise the heterogeneous nature of each subak based on the full probabilistic details of its systemwide uncorrelated principal components. This approach is more informative than simply using a single statistic such as the variance of these principal components to depict the nonuniformity within the individual subak, because these subaks may exhibit different internal dynamics. Furthermore, performing PCA on individual subaks to determine its intrinsic heterogeneity is also inadequate because only local information is being used without taking into account the global information that is available when PCA is carried out systemwide on the ensemble of all subak farmers.

ENERGY LANDSCAPE ANALYSIS

To construct the energy landscape, we have to fit the relative frequency of a set of subak states to a Boltzmann distribution (see SI Section E.). These subak states are coarse-grained states of the subak defined by its principal components. The energy landscape is formed over these subak states, with its topography directly proportional to the state's density.[7] The strength of the attractor for a given configuration of PCs in cluster of subaks is defined by its density, which appears as its depth in the energy landscape: the denser the state, the greater the depth. As the density of state weakens, the depth decreases. Consequently, this analysis provides a visual representation of the strength of the attractors and their basins of attraction that define the three regimes discovered by the subak-level PCA. Three clearly distinct basins emerge in the energy landscape (***Figure 8***, bottom). The dominant Attractor γ, with 16 subaks, has an energy of −3.07 (in arbitrary units), compared to higher energy, less stable Attractors α (−0.52, 2 subaks) and β (−0.52, 2 subaks). These basins reflect regions of increased stability, which we interpret as regimes, and their relative depths indicate their stability.

With the energy landscape determined, transition paths between attractors can be calculated. The idea here is similar to the evaluation of transition paths between metastable states (attractors) in chemical kinetics and protein folding problems (Best and Hummer., 2005), in that it is driven by a similar conceptual question

– what is the simplest set of changes that are required to move from one stable system state to another? Typically, such transitions are driven by noise in the system, which causes the system to overcome an energy barrier as it transits between the two attracting states. In our case, the noise arises from the variability of the social and ecological conditions. Instead of reaction coordinates as in the protein folding problem, our collective variables are the dominant principal components of the system. The transition path is the minimum energy pathway, which is also the most likely path between the attractors. From the energy landscape, we hypothesize that the transition pathway is one that gives the smallest difference between the variables that dominate the three principal components. The survey data then provides us with the empirical conditions to estimate the hypothetical transitions between regimes. We estimate that the descriptors that dominate along the transition paths are indicated by the absolute difference between the mean descriptor state of the two attractors (see analysis and color bands in **Figure 8**). On this basis, two contrasting paths between the cooperative Attractor γ and the other two attractors emerge. Social problems dominate the pathway from β to γ, and are negligible for α to γ. These balance out for α to β. Water availability dominates the transition path from γ to α, because it is a constant problem for γ subaks but essentially absent for α.

Transition paths are essentially a description of the necessary outcomes of some series of changes that lead a subak from one regime to another. While they do describe the simplest path between two regimes, without further work profiling the rate and manner of changes in attitudes we cannot predict how quickly a subak may move along a transition path, the order of changing attitudes required to move along it, or how closely individual subaks moving from one regime to another follow the probable average transition. It is therefore critical to explore the meaning of transitions by exploring the ethnographic and historical context of subaks in the three attractors.

The state of each subak which is determined by the mean responses of its farmers, is projected onto the first three

principal axes ($i = 1$, 2 and 3) to yield $\{d_i^1, d_i^2, \cdots, d_i^S\}$ where S is the total number of subak studied. We then follow the energy landscape analysis introduced in (Ezakietal., 2017) by converting these states into a sequence of binarized components $\{\sigma_i^1, \cdots, \sigma_i^S\}$. If d_i^S is greater than a threshold τ, $\sigma_i^S = 1$. Otherwise, $\sigma_i^S = -1$. The threshold τ is arbitrary, and we set it such that the conditional probability $P\left(\sigma_i^{S_1} = \sigma_i^{S_2} \middle| \left| d_i^{S_1} - d_i^{S_2} \right| \leq \epsilon \right)$ is maximized for all i, with $\epsilon = 0^+$. Thus, the state of a subak is given by a three dimensional vector $\sigma = (\sigma_1, \sigma_2, \sigma_3) \in \{-1,1\}^3$, where we have suppressed s. Note that there are 2^3 possible states in total.

From the binarized states of the S subaks, we compute the relative frequency with which each state is visited, $P_{empirical}(\sigma)$ (**Table 4**). We then fit the distribution to a Boltzmann distribution given by (Ezaki et al., 2017):

$$P(\sigma|h,J) = \frac{\exp\left[-E(\sigma|h,J)\right]}{\sum_{\sigma'} \exp\left[-E(\sigma'|h,J)\right]} \qquad (3)$$

where

$$E(\sigma|h,J) = -\sum_{i=1}^{3} h_i \sigma_i - \frac{1}{2}\sum_{i=1}^{3}\sum_{j\neq i} J_{ij}\sigma_i\sigma_j \qquad (4)$$

is the energy and $h = \{h_i\}$ and $J = \{J_{ij}\}$ ($i, j = 1$, 2, and 3) are the parameters of the model. We assume $J_{ij} = J_{ji}$ and $J_{ii} = 0$ for ($i, j = 1$, 2, and 3) and use likelihood maximization algorithm (see the Matlab codes section in SI for a sample code for the algorithm) to estimate the parameters of the model, i.e. h and J.

With h and J, we obtain energies of all states and construct a dendrogram by the following procedure. We enumerate local minima, i.e. the state whose energy is smaller than that of all neighbours. Here, we define neighbouring states σ and σ' as states which are only different at the third principal axis. For example, $(-1, -1, -1)$ and $(-1, -1, 1)$ are nearest neighbor states. We consider distance along the third principal axis to be the smallest because the third principal component is the least significant of the first three components in PCA. Based on this definition, the nearest neighbor states are states 1 and 2; states 3 and 4; states

STATE	1	2	3	4	5	6	7	8
σ_1	–1	–1	–1	–1	1	1	1	1
σ_2	–1	–1	1	1	–1	–1	1	1
σ_3	–1	1	–1	1	–1	1	–1	1
$P_{empirical}(\sigma)$	0.65	0.15	0.05	0.05	0.05	0.05	0.00	0.00
$P_{model}(\sigma)$	0.6487	0.1504	0.0505	0.0487	0.0505	0.0487	0.0005	0.0021
$E(\sigma)$	–3.07	–1.61	–0.52	–0.48	–0.52	–0.48	4.04	2.65

Table 4 Frequencies and energies for the 2^3 binarized states.

5 and 6; and states 7 and 8 (see **Table 4**). A local minimum would reside within one of these nearest neighbor states. Thus a connection from one energy minimum to another energy minimum has to occur on states that differ in at least the first two principal axis. Such a connection signifies a branch point of the dendogram and represents an energy barrier between the two energy minima.

Each local minimum has a basin of attraction in the state space, with each state belonging to one of the attractive basins. By repeatedly following a neighbouring state that has the smallest energy value, the associated local minimum can be reached. For a given pair of local minimums α and α', we consider a path connecting them as a transition path. The path connecting them includes a sequence of states that begin at state α and end at state α'. The largest energy value among the states on the path gives the energy barrier that need to be overcome for the transition to happen. With the information of all attractors and energy barriers between them, we construct a hypothetical two-dimensional landscape.

ADDITIONAL FILE

The additional file for this article can be found as follows:

- **Supplementary Information.** Here we describe our use of principal components analysis (PCA), Fisher Information and energy landscape analysis as well as results relating to them not covered in the main text. DOI: *https://doi.org/10.5334/ijc.1118.s1*

ACKNOWLEDGEMENTS

NOTES

1 Following the usage in ecology we refer to qualitatively stable attractors as "regimes". (Andersen et al., 2009)

2 A component Allee effect is a density-dependent process that reduces some component of fitness at low densities, which differs from demographic Allee effects in that the component Allee effect does not necessarily diminish population growth, because other fitness components might compensate. (Berec et al., 2007)

3 This survey built on the results of a prior study of eight subaks along a single river, with a much simpler questionnaire (Lansing et al., 2014)

4 Here Habermas' hierarchical distinction between "strategic action", "communicative action" and "discourse" becomes relevant. In strategic action, actors are interested in achieving the individual goals they each bring to the situation. In communicative action, speakers coordinate their action and pursuit of individual (or joint) goals on the basis of a shared understanding that the goals are inherently reasonable or worthwhile. Whereas strategic action succeeds insofar as the actors achieve their individual goals, communicative action succeeds insofar as the actors freely agree that their goal (or goals) is reasonable, that it merits cooperative behavior. (Bohman and Rehg, 2014)

5 The first appearance of the term subak occurs in the Pandak Bandung inscription of 1071 AD. The following year, the Klungkung C inscription includes a royal order calling for the re-measurement of the rice fields of the subak of Rawas, and lists the irrigated areas that belonged to this subak, which were located in at least eighteen communities (Lansing et al., 2009). After the conquest of north Bali by the Dutch in the 19th century, colonial officials also emphasized the autonomy of the subaks. After surveying the conquered kingdoms in the 1880's, the senior Dutch colonial official concluded: "The explanation of the amazingly high standard of rice cultivation in Bali is to be found in Montesquieu's conclusion that 'the yield of the soil depends less on its richness than on the degree of freedom enjoyed by those who till it'". See (Liefrinck, 1969).

6 For the past decade, the area of rice paddies managed by subaks has declined by approximately 1000 hectares per year since the year 2010, when the total was 86,000 hectares. (Windia et al., 2017)

7 The density of a state is defined as the number of subaks per state.

COMPETING INTERESTS

The authors have no competing interests to declare.

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