A robust budding model of Balinese water temple networks

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Abstract

Ethnohistory, genetics and simulation are used to propose a new 'budding model' to describe the historical processes by which complex irrigation communities may come into existence. We review two alternative theories, Wittfogel's top-down state-formation theory and common-pool resource management, and suggest that a budding model would better account for existing archaeological and ethnographic descriptions of a well-studied network of irrigation communities on the island of Bali. The budding model is supported by inscriptions and ethnohistorical documents describing irrigation works in and around the drainage of the Petanu River, an area with some of the oldest evidence for wet-rice agriculture in Bali. Genetic analysis of Y-STR and mtDNA shows correlated demographic histories and decreased diversity in daughter villages, consistent with the budding model. Simulation results show that the network of irrigation communities can effectively adjust to repeated budding events that could potentially shock the system outside the parameter space where good harvests can be maintained. Based on this evidence we argue that the budding model is a robust explanation of the historical processes that led to the emergence and operation of Petanu irrigation communities.

Keywords

Bali; irrigation; genetics; pre-colonial; inscriptions; complex adaptive systems.

Introduction

Two models dominate the social science literature on irrigation. The older of the two focuses on the power-centralizing effects of large-scale irrigation in the context of state formation, and takes its inspiration from the work of Karl Wittfogel. A more recent approach examines 'community-based irrigation systems' as common-pool resource (CPR) institutions, using tools from microeconomics and game theory (Bardhan and

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Dayton-Johnson 2002). Our goal in this article is to clarify and critically evaluate a third model that has emerged from our research on the water management groups (*subaks*) and water temple networks of the Indonesian island of Bali. Using new archaeological and genetic data and a computational simulation, we assess how well a 'budding model' explains the expansion of wet-rice irrigation in a well-studied region of Bali. A further goal is to clarify the model so that researchers working on canal irrigation systems in other parts of the world can evaluate whether some or all of it may apply to the cases they study.

The budding model that we propose here describes an historical scenario in which canal irrigation systems expand downstream as a result of local initiatives. As these systems grow in size and complexity, they trigger environmental processes to which the farmers react. Successful solutions are rewarded with better harvests, generating demographic pressure for further expansion to the limits of the available irrigation water. Mere trial and error can lead to a flexible multi-scale managerial system, enabling groups of farmers to improve their control of ecological processes such as water flows and pest management. There is no role for top-down control in this model; nearly any intervention from outside the network structure is at best neutral and is more likely to reduce harvests. Consequently, the role of the state is confined to taxation and/or encouraging the expansion of the system (Lansing 2005).

The resulting managerial structure may be viewed as a nested hierarchy of institutions managing common-pool resources at multiple scales. Standard models of community-based irrigation management lack this nested, multi-scale structure; they also fail to consider the effects of coupled human-environmental interactions occurring through time. For these reasons, we suggest that the budding model is better understood as an emergent *complex adaptive system*, which may encompass hierarchies of community-based CPR institutions (Lansing 2003). This perspective shifts the analytical focus of the model away from the social dynamics of cooperation (the central question for CPR models) to the emergence of structure in space and time, as a patchy environment responds to the farmer's decisions about water scheduling. Cooperation remains important in our budding model, but the scope of the question broadens to consider the ecological consequences of cooperation at different spatiotemporal scales. In the simulation model, cooperation becomes an effect that is predicted to emerge at varying scales depending on the underlying ecological dynamics.

This type of model raises some new questions, which we have begun to address in earlier publications. For example, how do these canal irrigation systems expand? And how robust are they to perturbations, ranging from environmental variation to the effects of growth? Here we draw from our earlier work to suggest answers to these questions, and provide pointers to more extended discussions. We begin by reviewing what is known about the origins and spread of irrigation in Bali. Next we narrow our focus to a region of northern Gianyar which serves as an empirical case. We review the results of a study of the genetic population structure of the farmers in the region, which offers insights into the history of the formation of farming communities. The paper concludes with a mathematical analysis of the robustness of the budding model to environmental processes (water shortages and agricultural pests) during a period of expansion.

The origins of wet rice cultivation in Bali

The oldest direct evidence for rice on Bali is a radiocarbon date of 2660+/−100 BP at the site of Sembiran on the north coast. However, this date is from rice husk used as temper in a pottery sherd of probable Indian origin, and thus does not prove that rice was consumed on Bali at that time (Bellwood et al. 1992). More useful are the rice phytoliths found in the sediments at the same site, indicating likely cultivation by 1 AD. The earliest of all the dated inscriptions (Sukawana A I, from AD 882) mentions irrigated rice fields (*huma* in Old Balinese), and the third dated inscription (Bebetin A I, from AD 896) mentions irrigation tunnel engineers (*undagi aungan*). The tunnelers are found in a list of professional artisans who worked for pay, suggesting that at this early date there already was enough demand for irrigation system construction to support them as independent specialists, since no evidence connects them with elite courts or village administrations (Ardika 1994: 9–10; Ardika and Beratha 1996: 23, 27, 49, 1998: 13; Christie 1992: 16, 2007: 250). Tunnel experts are mentioned again in the AD 1022 inscription of Batuan, which also contains the first of many mentions of the word *sawah,* the usual term for irrigated rice fields in Old Javanese (Ardika 1994: 9; Ardika and Beratha 1998: 66, 73; Setiawan 1995: 101–2). The same inscription also refers to the water allocation role of an official called the *makaser* of Air Gajah (Ardika and Beratha 1998: 74; Christie 1992: 15, 2007; Sukarto 1986: 59–60).

The first appearance of the term *subak* is as the root of the word *kasuwakan* in the Pandak Bandung inscription of 1071 AD (No. 436: Ardika 1994: 27; Ardika and Beratha 1998: 313; see also Sukarto 1986: 32–3; Setiawan 1995: 104–5), but it is difficult to tease out much information on the productive and religious roles of the institution from the text. The following year (1072 AD), the terms *kasuwakan* and *kasubakan* are used interchangeably in the inscription Klungkung C (No. 438, also known as the charter of Er- rara I: Sukarto 1986: 35–6, 51). This inscription discusses a royal order calling for the re-measurement of the rice fields of the *kasubakan* of Rawas, and lists the irrigated areas that belonged to this subak, which were located in at least eighteen communities. As Christie notes, this suggests that *subaks* were boundary-crossing entities by the eleventh century. She also examines the list of nineteen *kasuwakans* given in the 1181 AD charter of Udanapatya (No. 628, Pengotan C II), pointing out that, in her words, ‘the *kasuwakan* names are different from the names of the villages referred to in the same charter, so it does appear that their areas of jurisdiction cross-cut those of the villages’ (Christie 1992: 15, 2007; Sukarto 1986: 33–51). She further observes that the dissected nature of the Balinese landscape requires that irrigation systems frequently tap rivers and springs at points that lie within the lands of villages located well upstream from those that benefit from the water. The construction of boundary-crossing channels and tunnels could provide an impetus for the development of irrigation societies that are largely autonomous from other social institutions. In addition to the 1072 and 1181 AD cases just noted, in this context it is also significant that the 1022 Batuan inscription describes an irrigation system that brought water to ‘Baturan’ from ‘Pujung Ngaji’ and ‘Air Gajah’. These three place-names are usually associated, respectively, with the modern village of Batuan where the inscription was found, the neighborhood of Pejengaji 14km to the north of Batuan in the village of Tegallalang and the monumental site of Goa Gajah in Bedulu, 6km north of

Batuan (Setiawan 1995: 111, 133; Ardika and Beratha 1998: 74). If these place-names are correctly interpreted, the distances involved make this an almost certain case of another boundary-crossing irrigation channel.

Irrigation in the upper Petanu

We turn now to the *subaks*, irrigation systems and water temples that presently exist in the region of southern Bali where some of the oldest evidence for irrigated rice is found, along the Petanu river (cf. Scarborough et al. 1999, 2000). We focus on a congregation of about fifteen *subaks* that bear primary responsibility for the rituals held at a regional water temple, Pura Masceti Pamos Apuh. An inscription provisionally dated to the twelfth century mentions contributions made by the irrigation leaders of several of them (Sebatu, Kedisan) to ceremonies in the village where their water originates, implying the presence of a shared water temple by that time (study of this inscription is in progress: Schoenfelder et al. n.d.).We begin with the physical irrigation system. These *subaks* are located at relatively high elevation, close to the sources of the streams that feed the Petanu river. Monsoon rains falling on the volcanic slopes have sliced deep channels for the streams and rivers in the landscape, so the main engineering challenge for ancient farmers was to find a way to transport the water from these sunken streams to terraced hillsides at lower elevations. Their solution was to build weirs, using logs, earth and stones, and divert the flow into tunnels, which emerge some distance downslope and convey the water through branching canals to the rice terraces.

Two key features stand out with respect to the engineering aspects of this system. First, in cross-section these tunnels are all nearly the same size, just large enough for a man to wield a pickaxe at the rock face. Thus the size of the tunnels was not adjusted to the desired flow volume; instead it depended on the technology used to construct them. Once a weir and tunnel are in place, they may capture more water than is needed for the first blocks of rice terraces. If so, the canals can be lengthened downstream as needed, until all the water is eventually put to use. This leads to the second point. Expansion of the area under irrigation was accomplished not by enlarging existing tunnels but by adding new weirs and tunnels, often located only a short distance downstream from an existing weir. This was feasible because the streams are very quickly recharged by the annual cycle of heavy rainfall that is absorbed by the porous volcanic terrain. The construction of such a tunnel is shown in the film *The Goddess and the Computer* (Lansing and Singer 1988).

This method of expansion – filling in the landscape with uniform-sized weirs and tunnels – is typical of *subaks* at the higher elevations, where rainfall is heavy but the streams and rivers are small. Small weirs tap into the streams and springs at many sites, and irrigation canals crisscross the territories of hamlets and villages. For reasons that will be explained below, the ecology of wet rice cultivation rewards the farmers for coordinating water flows not only at the level of single weirs, but in clusters of adjacent weirs. In this region, such coordination is accomplished at the regular meetings of *subak* heads (*pekaseh*) who form the congregation of the Pamos Apuh water temple. To this temple the farmers bring offerings to the goddess of the lake, Dewi Danu, who 'makes the waters flow' and other deities. By means of these offerings, the farmers and *subaks* acquire the right to a share of flowing water, the gift of the goddess. This principle is given physical reality by means of proportional dividers in the canals, which instantiate a fractional division of the water flows in units called *tektek*. Each *subak* in the congregation of the Pamos Apuh temple has the right to a water share for so long as they contribute offerings and support (*soewinih*) to the temple, proportional to their *tektek* allocation. The responsibility for delivering these offerings and contributions each year falls on the *pekaseh*. The office of *pekaseh* (*pakasaih*) is mentioned in ancient royal inscriptions.

In mid-July 1997 and 1998, at the height of the dry season when competition for water is keenest, we measured irrigation flow volumes for most of the canals leading to the *subaks* in this system, and compared them with their *tektek* allocations as reported by *pekaseh* (Table 1). The r correlation of flow (liters per second) to *tektek* is 0.95, so the *tektek* shares do correspond to actual flow volumes.

We measured flow volumes at bi-weekly intervals in 1997–8 at the tunnel exits (irrigation intakes) for the Sebatu and Bayad irrigation systems as shown in Figure 1. Downstream *subaks* are at a disadvantage because *tekteks* are measured at the head of the

Table 1 Measured flow volumes at the intake to primary canals (in liters per second) compared with water rights based on proportional shares (*tektek*), July 1997 and 1998

Subaks	*Flow*	*Tektek*
Jati	71	1.5
Bonjaka	102	2.5
Bayad	198	7.0
Tegal Suci	190	7.5
Pujung	198	8.0
Kedisan	214	8.0
Timbul & Calo	460	21.0
Jasan & Sebatu	368	16.0

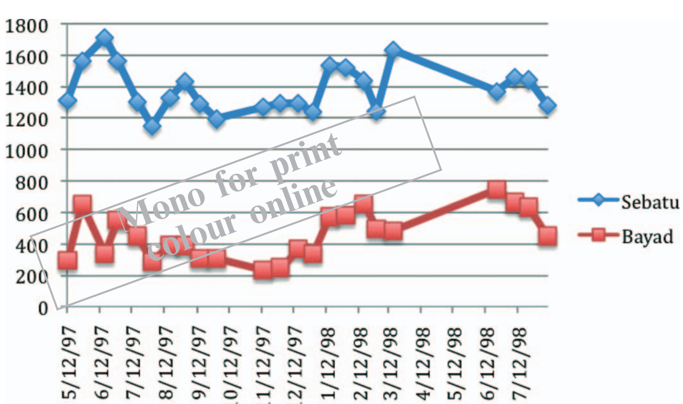

Figure 1 Irrigation flows at the exit from the Sebatu weir irrigation tunnel, 1997–8, measured with a flow meter in units of liters per second.

tertiary canal, which may be located kilometers upstream from the rice terraces. The amount of water reaching each *subak* on 17 July 1996 is shown in Table 2; the average was 2.8 liters per second per hectare (standard deviation 0.9 liters/sec/ha). Due to the length, complexity and fragility of the canals, downstream *subaks* suffer losses from percolation and evaporation. Consequently the average quantity of water delivered to downstream *subaks*, such as Kebon, Kedisan Kelod and Pakudui, is somewhat larger than the flow to the upstream *subaks*, such as Timbul and Sebatu. However, downstream *subaks* routinely take advantage of excess or borrowed flows from upstream neighbors and local springs and seeps. Water from these sources, called *tirisan*, is not included in the water rights defined by *tektek*, which pertain only to the flow in the major canals. But *tirisan* is vital for most downstream *subaks*, to make up the deficit caused by percolation and seepage losses in the canals.

Larger and more complex engineering projects were formerly undertaken by groups of *subaks* downstream, where the rivers become larger and there is more land available for rice paddies. Early in the twentieth century, when the Dutch colonial government assumed control of south Bali, responsibility for the construction and maintenance of large dams passed to government civil engineers (Plate 1).

The Dutch completed their conquest of south Bali in 1908, and in 1912 the colonial government began to map the *subaks* and irrigation systems of south Bali. An irrigation engineer, O. W. Sörensen, described the construction of large storage dams by the *subaks* in a 1921 engineering report:

> Because of the deep ravines, dams that hold the water up high are necessary to make irrigation possible. Especially in the district of Gianyar, we find dams of great height (up to 35 meters). In most cases as a result of the irregular terrain the digging of tunnels is necessary, often of respectable length. From there the water follows an open canal to

Table 2 Average measured irrigation flows and flow volume per hectare of *sawah* in some *subaks* belonging to the water temple Masceti Pamos Apuh, during the dry seasons (July–August) 1997–8

Source	*Subak*	*Flow*	*Sawah*	*Flow/sawah*
Tegal Suci main canal		190	25	7.60
Sebatu tunnel exit		1890	608	3.11
BS1	Jasan & Sebatu	368	117	3.15
BS2	Pujung Kaja	87	33	2.62
BS3	Pujung kelod	111	50	2.22
BS4	Pujung kaja	120	64	1.88
BS5	Kedisaan kaja	131	29	4.52
BS5	Pujung kaja	19	11	1.77
BS6	Kedisan kaja	83	35	2.37
BS6	Kebon, Kedisan kelod, Pakudui	337	145	2.32
Timbul & Calo main canal		460	156	2.95
Bayad main canal		198	97	2.04
Jati main canal		71	17	4.15
Bonjaka main canal		102	28	3.66

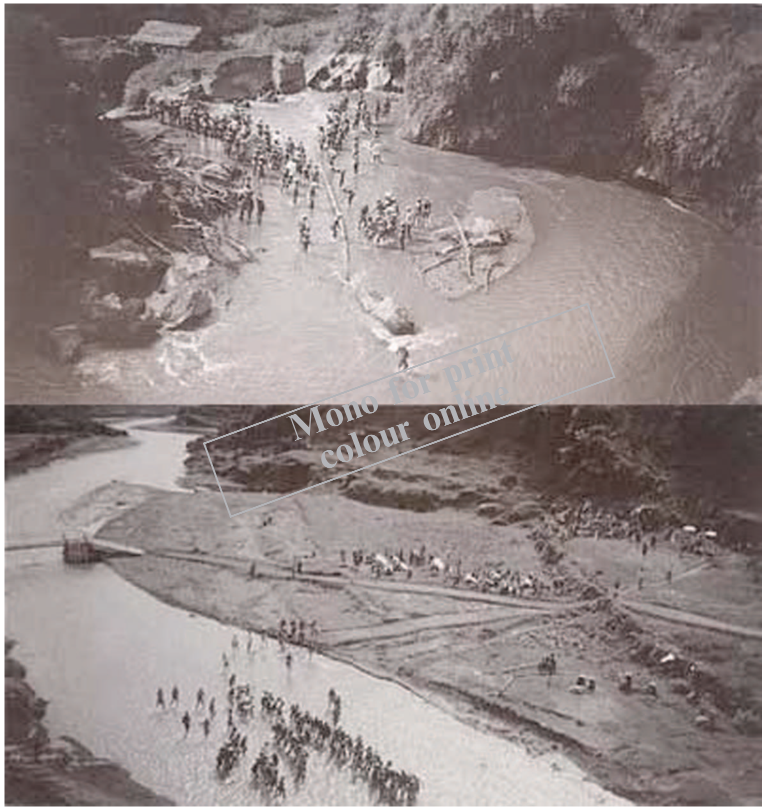

Plate 1 Dutch photos taken during a visit of the Governor General of Netherlands Indie in 1925 to view the construction of the Pejeng Dam in Gianyar.

> reach the *sawahs*. The maintenance and repairs of the dams and canals rests with the *subak* members, who at the charge of the *pangloerah*, the head of one or more *waterschaps* [water districts], and under the supervision of the heads of the *subaks*, the *pekasehs*, must execute the necessary labor. The same with the construction of new dams: the execution and the costs are borne by those who later will profit from the dam. . . . The best tunnel builders are found in Klungkung and they enjoy a very good reputation all over Bali, so the help of these specialists is always invoked for that kind of work.
>
> (Sörensen 1921: 116, trans. JSL)

The *pangloerahs* were local officials, essentially village heads, responsible to the colonial government; their authority extended over a *pangloerahan* (an officially recognized, territorial 'village'). Sörensen comments that the *pangloerah*'s areas of administrative responsibility usually did not correspond with the territorial boundaries of the *subaks*, which caused some difficulties:

> The areas of the *pangloerahans* containing several *subaks* are in many cases formed following the (administrative) districts, so not, as would be rational, according to

> irrigation areas. Therefore one often sees that in one irrigation area several *pangloerahs* are engaged. To improve this situation, that is to form the *pangloerahanans* not according to (administrative) districts but natural irrigation areas, the irrigation service has been charged, in consultation with the Binnenlands Bestuur [interior department], and the indigenous heads in question, to reorganize anew the *pangloerahans*. The reason why [administrative] district borders were followed with the introduction of the job of *pangloerah* in the different [administrative] subdivisions can be ascribed to the fact that this title-holder among other things also functions as a tax collector.
>
> (Sörensen 1921: 119, trans. JSL)

Sörensen provided diagrams, photos and descriptions of some of the large dams constructed by the *subaks*. Dam construction began in the dry season when flows are low, with the construction of a row of baffles or obstacles in the river where sediment would build up. Larger tunnels were dug on one or both sides of the dam, and the flow diverted so that the dam could be raised and strengthened. These dams were vulnerable to the high flow volumes of the rainy season. Sörensen comments:

> The normal principle followed by the Balinese in the construction of a *prise d'eau* is an earthen blocking dam in the river; the dam in general is built up quite a bit above the *banjir* (flood) height and the top is planted with coconuts, alang grass etc. To be able to get rid of the *banjir* (flood) water, on one of the banks a canal is dug that serves as an overflow duct. The dams that are built rather solidly hardly ever suffer from overflow since they are sufficiently high above the height of the *banjir*; the weak point of the Balinese waterworks lies in the overflow canals.
>
> (Sörensen 1921: 116, trans. JSL)

These large dams could retain a large quantity of water to be released in the dry season. A small water temple was placed atop the larger dams. Sörensen provides sketch maps and photos of some of the most impressive dams:

> The old indigenous dam of Badoeng consisted of a broad approximately 40 meter high earthen dam with two canals for overflow, one on the right and another on the left bank of the river, and a water outlet which delivered water for about 478 *bouw sawahs*.
>
> (Sörensen 1921: 118, trans. JSL)

In summary, two technologies for irrigation expansion existed in pre-colonial Bali. Upstream, small weirs proliferated, which shunted water into tunnels and irrigation canals that could extend for several kilometers, often involving additional tunnels and occasional aqueducts. Downstream, larger storage dams were created by groups of *subaks*. Expert tunnel builders supervised the construction of both systems, while labor and other costs were provided by those who expected to profit from the flow. The organization of these projects was in the hands of the *pekaseh*, or *subak* heads, who are also mentioned in ancient inscriptions. In colonial times the *pangloerah*, or village heads appointed by the Dutch, had nominal authority over irrigation and agriculture, and collected agricultural taxes. But as in ancient times, the irrigation systems and subaks typically extended beyond the boundaries of *pangloerahans*. After the end of the brief colonial era, village heads (the successors to the *pangloerahs*) lost any administrative role in irrigation.

An alternative scenario for the expansion of irrigation

As noted above, irrigation systems along the Petanu river are among the oldest in Bali, frequently mentioned in eleventh- and twelfth-century inscriptions. These inscriptions suggest that, apart from taxing harvests, there was little or no royal involvement in irrigation. But a different scenario has been suggested for a region to the west. The kingdom of Mengwi came into existence early in the eighteenth century. According to H. Schulte Nordholt, at that time Mengwi was largely forested. The first king built a dam in the Sungi river, and subsequently played an important role in irrigation management.[1] Schulte Nordholt writes that, although 'there is no accurate information' on the villages that existed in Mengwi at the time the dam was built, circa 1750, the picture that emerged from attempt to reconstruct the demography 'is that of a thoroughly fragmented settlement ... [these villages] would not have been able to clear large tracts of woodlands or to construct irrigation works miles from home' (Schulte Nordholt 1996: 57).

> In the course of the eighteenth century the sawah area probably expanded under the encouragement of the Mengwi dynasty. But this did not mean that the king centrally controlled the whole. If his control of manpower in the region was limited, his say in the matter of irrigation was no less so. The example of Sibang shows that the larger satellites each managed their own irrigation works and the concomitant taxes and servitude. The effect of this was that the position of the satellites in relation to the centre was quite strong. The satellites were micro kingdoms.
>
> (Schulte Nordholt 1996: 61)

Thus, according to Schulte Nordholt, the mobilization of labor to expand irrigation into previously forested regions of western Bali was accomplished by the lords of these 'micro kingdoms'. This scenario contrasts with the budding model we have proposed for the Sebatu region, in which irrigation works were created by farmers, with new settlements budding off downstream as a result of demographic pressure. The budding process makes specific predictions about the population genetic structure of the villages, and can therefore be tested through molecular genetic analysis. If the expansion of irrigation was accomplished by the farmers themselves, then population movements of males (patrilineages) would occur as a result of demographic pressure leading to the formation of new daughter settlements close to parent villages. The budding model would thus predict the formation of small communities located along irrigation systems, with the oldest settlements located at the irrigation outtakes nearest to the most ancient weirs or springs. Conversely, if large, multi-*subak* dams were built in virgin territory, there would be no reason for farming communities closest to those dams to be older than those located further downstream. In 2001 we began to gather the genetic data needed to test these hypotheses, a comparison of *subaks* located in both regions (the Sungi river in Mengwi, and the upper Petanu).

Genetic tests of the budding model

We analyzed genetic markers from 587 Balinese men for this study. One group consisted of 287 farmers who belong to thirteen *subaks* associated with the Pamos Apuh water temple on the upper reaches of the Petanu river. The second consisted of 120 farmers belonging to eight *subaks* located along the Sungi river in the former kingdom of Mengwi. While the Pamos Apuh *subaks* are tightly clustered, the Sungi subaks are spread along the full length of the river. The average geographic distance between the Pamos Apuh *subaks* is only 3.2km; it is 13.9km for those along the Sungi river (Fig. 2).

The results of genetic analyses on these *subaks* are fully explored in Lansing et al. (in press), but we summarize the relevant findings here. *Subaks* located at the furthest positions upstream on their respective irrigation systems on both rivers demonstrate greater levels of genetic differentiation and diversity, suggesting that they came into existence before their downstream neighbors. The budding deme model predicts decreases in diversity among subpopulations as the process continues in time. Consistent with this prediction, diversity parameters were also higher for the older Sebatu subaks located furthest upstream in their respective irrigation systems (Sebatu, Pujung, Timbul, Bayad) than those known to be younger (Jati, Jasan, Bonjaka, Tegal Suci). There was a strong correlation between Y-STR and mtDNA structure in the Sebatu *subaks* (r = 0.629). There

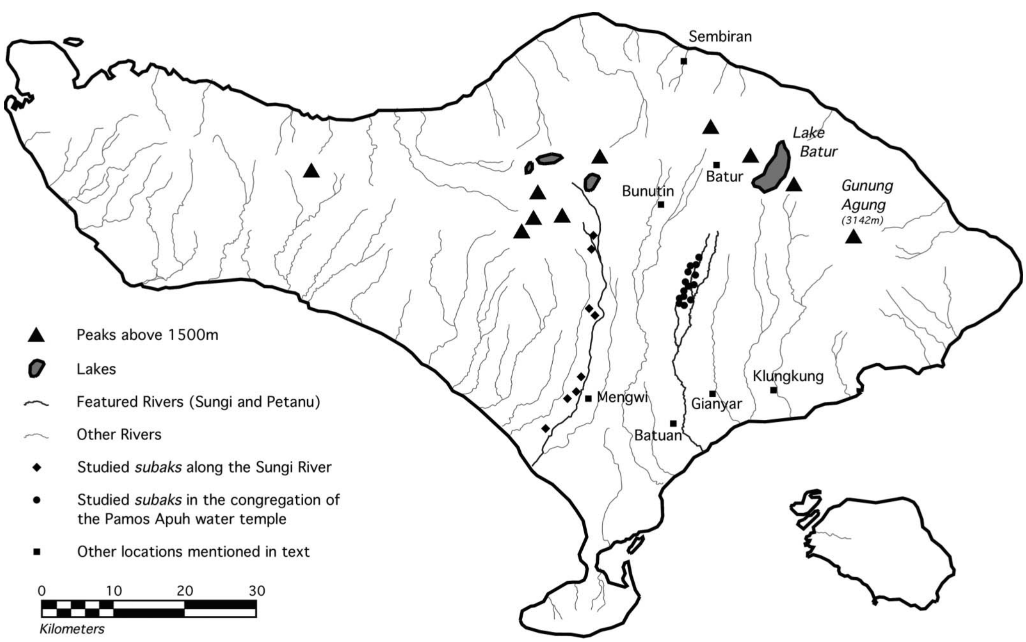

Figure 2 Map of Bali, showing Sungi River and Pamos Apuh *subak* (irrigation society) DNA sampling sites.

were also strong correlations between Y-STR variation and geography (r = 0.541), and mtDNA and geography (r = 0.361), possibly reflecting the same events in population history. No such correlations existed for the Sungi *subaks* or the all-Bali sample (Lansing et al. in press).

Just as new *subaks* develop downstream from pre-existing networks, the budding model suggests that new villages may form when individuals move downstream from pre-existing upstream communities. Described more formally, the budding model suggests that some proportion of individuals from an upstream group creates a new community immediately downstream (Fig. 3A). This model can also be viewed as a process that unfolds through time (Fig. 3B). An ancestral upstream community (N_A) splits at some time T. While most individuals remain at the ancestral location upstream (N_U), a smaller number forms a new community downstream (N_D). The proportion of individuals founding the new community can be modeled by a single demographic parameter S, which records the proportion of the ancestral community that 'splits' from the upstream group to found the new downstream group. This parameter can vary from zero to one. If each daughter population forms by equal division of the ancestral community, S is a half. Conversely, in a strong budding event, few individuals found the new community, and S approaches zero. For completeness, migration is allowed up and down the water system following the formation of the two daughter populations. Given sufficient genetic sampling, the parameters of this model can be inferred directly from molecular data, as described above.

We assume here that men drive the formation of new communities, and therefore focus on genetic markers that reflect male history (i.e. the Y-chromosome). An ongoing study is also examining mitochondrial DNA and autosomal markers, which will be reported elsewhere. We sampled between twenty and forty men from each of five upstream-downstream community pairs located along the Petanu River in central Bali: Sebatu-Pujung, Pujung-Pakudui, Pujung-Kedisan, Kedisan-Kebon and Timbul-Calo (Fig. 4). Each individual was genotyped for twelve length-variable microsatellites on the

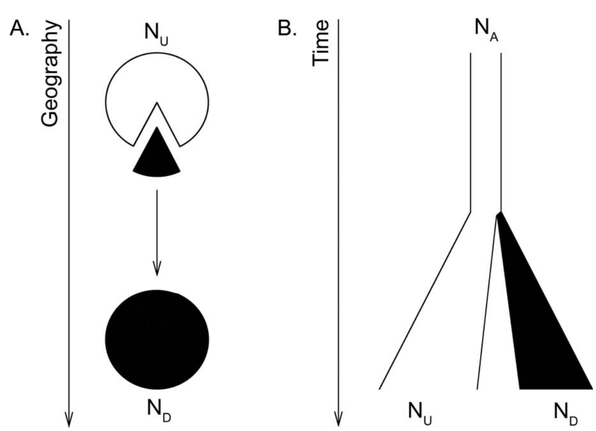

Figure 3 Model of population budding along a water system. A. Geographical model: a small number of individuals split from an upstream community (N_U) to form a new downstream group (N_D). B. Temporal model: a small number of individuals split from an ancestral upstream community (N_A) to form a new community downstream (N_D), while most individuals remain at the upstream location (N_U).

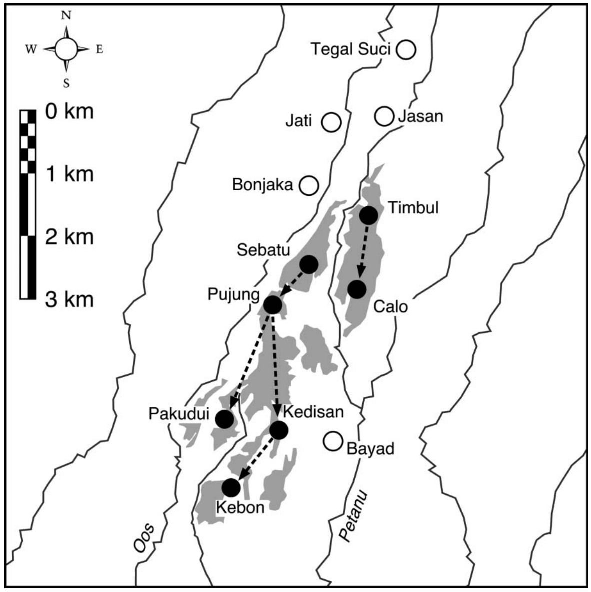

Figure 4 Locations and water relationships of subaks on the Petanu River. Dashed-line arrows between closed circles schematically depict channel links between the *subaks* of the two multi-*subak* irrigation systems in the study area; the approximate extents of the irrigated fields for these systems are shown in gray. Open circles indicate the locations of single-*subak* irrigation systems from which DNA samples were likewise obtained. All shown rivers flow south.

Y-chromosome, which evolve rapidly enough to capture recent demographic history. Karafet et al. (2005) present more detailed information on these samples, and their relationships to other communities on Bali and elsewhere in Indonesia. We determined parameters of the budding model described above independently for each upstream-downstream community pair using the coalescent software *IM* (Hey 2007). This inference method is described elsewhere (Hey 2005; Hey and Nielsen 2004; Nielsen and Wakeley 2001). Not all community pairs were sufficiently informative to infer the split parameter S with certainty, but they paint a preliminary picture of past relationships between adjacent communities on the upper Petanu River.

We find that some community pairs formed through a strong budding process, as typified by the communities of Pujung and Kedisan (Fig. 5). Kedisan lies immediately downstream from Pujung on the same water system. The maximum likelihood estimate for the Kedisan splitting parameter ($S = 0.024$) implies that only ~ 2 per cent of men in the community ancestral to Pujung and Kedisan moved downstream to form the new community of Kedisan; most of the ancestral population remained at Pujung. As is common in demographic inference, confidence intervals are large. However, the maximum likelihood estimate is consistent with two or three unrelated men, or more likely a larger number of paternally related families, leaving the ancestral community at Pujung to form a new community at Kedisan. Following the budding process, sporadic migration (on the order of one individual every few generations) occurred back upstream to the ancestral community, but there is no evidence of further migration downstream. This may reflect men exercising familial rights to land in the ancestral (i.e. upstream) village.

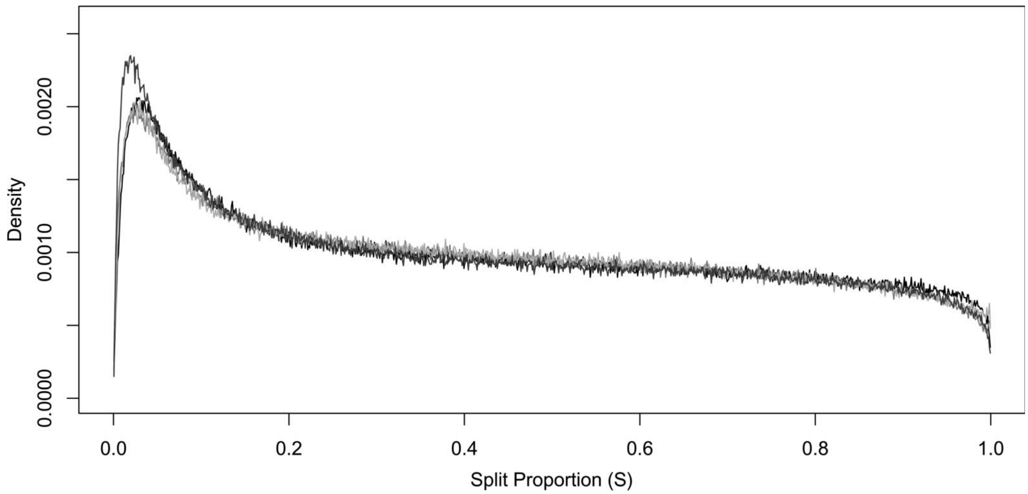

Figure 5 Probability curve of the splitting parameter *S* for Kedisan, the community immediately downstream from Pujung in the Sebatu water system. Each differently shaded line represents the marginal posterior probability from an independent analysis of the Pujung-Kedisan Y-chromosome microsatellite dataset.

Kedisan-Kebon and Timbul-Calo show near identical patterns to Pujung-Kedisan, and therefore probably reflect the outcome of similarly strong budding processes. Importantly, however, not all villages seem to have formed in this way. The Sebatu-Pujung and Pujung-Pakudui pairs buck this trend; ancestral upstream communities appear to have contributed a much larger proportion of men to downstream villages, which do not clearly result from a simple budding process. This may mean that upstream villages were not ancestral to communities immediately downstream in these two cases or that these two downstream communities did not form by population budding. Two accounts of modern village formation may be relevant in this context. The first case concerns the formation in 1977 of a new *subak*, Bunutin. Issues of land ownership drove the formation of a new subak with dual affinities, seventy families from the downstream village of Bunutin and thirty-three families from the upstream village of Ulian (Jemet 1991: 44; Schoenfelder 2003: 56). Although it is important to distinguish village from *subak*, similar arrangements in the past may have led to close family relationships, and subsequently the development of new communal villages. The second case concerns the village of Batur, which in 1947 divided into two new communities, North and South Batur. Political divisions, not political collaboration as for Bunutin, drove the formation of South Batur, but both cases ultimately represent the same genetic outcome – new communities formed without strong population budding. Clearly, the process of community formation is complex, and we anticipate that ongoing genetic studies will shed more light on this. A key point is that, although a strong budding fits some villages on the Balinese water systems, it does not apply to them all.

Although village formation can form in ways other than population budding, there is little evidence that the formation of new *subaks* is anything but a simple downstream budding process. Simulations with population budding show how this complex system may have developed over time. The *subaks* of the Sungi river do not show clear evidence of a budding process; this could be due either to their lesser age compared to the *subaks* of Sebatu, or to greater royal involvement in their formation.

Simulation tests of the budding model

In earlier studies we have shown that the water temple networks that enable the *subaks* to coordinate irrigation and cropping schedules can improve harvests by reducing losses due to pest infestations or water shortages. Here we consider the ecological consequences of the budding model. Could these networks become easily trapped or frustrated in a sub-optimal state, so that some external impetus would be needed to force the system to expand? To explore this question, we constructed a simulation model that is a stylized representation of the Sebatu irrigation system, including fourteen *subaks* of varying sizes arranged in two identical watersheds of seven *subaks* (Fig. 6). It is based on the main components of the Lansing-Kremer irrigation model (Janssen 2007; Lansing and Kremer 1993; Lansing and Miller 2005). The model can be run as a complete functioning network where all *subaks* are active or in an evolutionary mode that begins with a single active *subak*.

Each watershed shares a single source of irrigation water. There are no water flows between watersheds, but pests can migrate between adjacent *subaks* lying in different watersheds. In the evolutionary mode downstream *subaks* are created at parameterized intervals, in order 2 through 14. One time step in the model represents one month, and it takes three months for a crop of rice to mature. There is a maximum of three crops per year, and *subaks* may choose among five cropping patterns (irrigation and planting schedules). When a *subak* has rice on the field, it requires an amount of water proportional

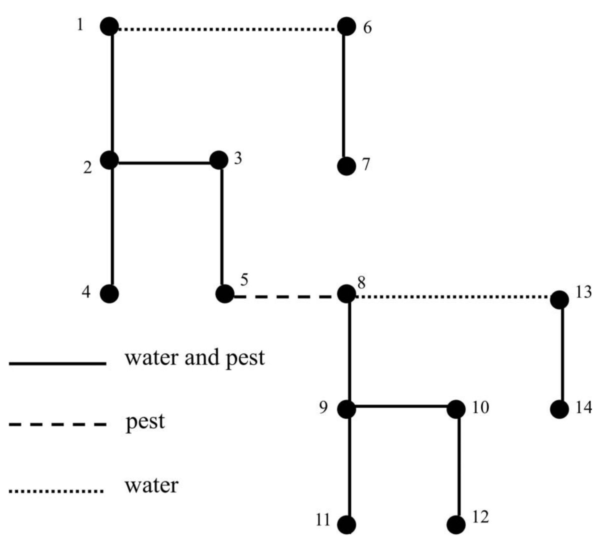

Figure 6 Irrigation network of budding model consisting of two watersheds (nodes 1–7 and 8–14, respectively). Irrigation water enters the system only at nodes 1 and 8.

to its size. The amount of water available for a *subak* is the residual after any upstream *subaks* fully irrigate their active crops. When a *subak* needs more water than is provided by its upstream neighbor, all *subaks* supplied by the upstream neighbor receive the same reduction of water supply. The fraction of demand that is not met defines water stress. Harvests can also be reduced by damage from pests. Each *subak* has a pest density, *p*. Pests grow much more quickly on a growing field of rice than on a fallow field, and can migrate from a *subak* with higher concentration to adjacent *subaks* with lower concentrations (see also Janssen 2007).

Cropping plans are randomly assigned at the beginning of each simulation. Each year *subaks* evaluate their harvest and may update their cropping plan to increase their production. Each *subak* compares its harvest with adjoining neighbors and may adopt the plan of a more successful neighbor. This decision depends on how much better the neighbor's harvest is – the 'threshold for imitating neighbor' (Fig. 7). There is also an innovation parameter: when a *subak* performs worse than the average harvest within its watershed there is a small probability that it will randomly change its cropping plan.

The parameter space is explored by varying the parameters in a systematic way using budding time (0, 5 and 10), the probability of innovation (0.001, 0.002, 0.003, 0.004 and 0.005), water input (75, 100 and 125), pest dispersal rate (0, 0.2 and 0.4), pest growth rate (2, 2.2 and 2.4) and the imitation threshold (0, 0.2, 0.4, 0.6). For each of the 1620 combinations 100 simulation runs were performed. Each model is run for 200 years (2400 months). The harvest per unit area is calculated by dividing the total harvest by the maximum possible yield of all *subaks* using the most intensive cropping pattern. Figure 8 shows the average harvests for a network that buds (creates new *subaks*) every five years.

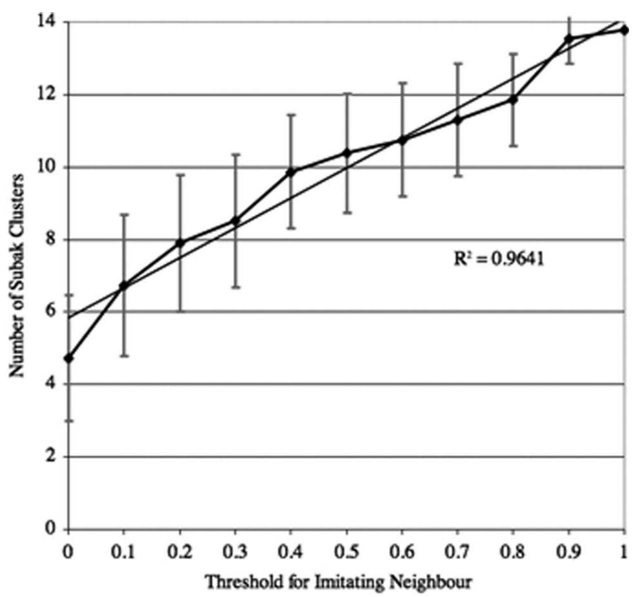

Figure 7 Strong correlation exists between a farmer's imitation threshold and the number of *subak* clusters. As the threshold is increased farmers are more resistant to adopting a neighbor's cropping pattern. This increases network fragmentation and may have the ecological effects of increasing pest levels or reducing water stress.

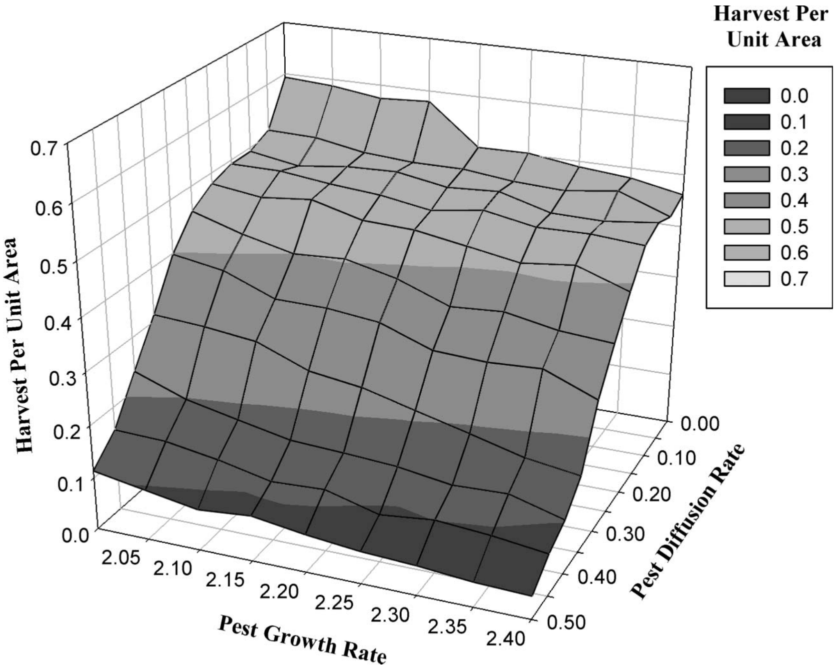

Figure 8 The response of average harvest per unit of area for fourteen simulated *subaks* to varying ranges of pest diffusion and pest growth rates. Harvest per unit area is expressed as a percentage of maximum harvest given the most intense cropping pattern and no damage due to pests or water stress.

When pests do not grow quickly or diffuse to other *subaks*, harvests depend only on water availability. With sufficient water available a high relative production can be derived. The results are most sensitive to the pest diffusion rate.

Using these simulations we explore the relationship between a full network and an evolving network. Figure 9 compares annual harvests between a budding network and complete *subak* networks. Each simulation was run for 200 years and reported harvests are the average of 100 replications. The following parameter settings were used: water input (100), pest growth rate (2.2), pest dispersal rate (.2), probability of innovation (.02) and imitation threshold (0). Because the productive capacity of the complete network is higher than that of an evolving network until all fourteen *subaks* are active, we compare the productive efficiency per unit area under cultivation as a percentage of the maximum possible yield per unit area. In the complete network the harvest initially declines due to high pest levels, but after about thirty years it reaches its maximum harvest levels. In the budding network, productive efficiency dips whenever the *subaks* reconfigure their cropping patterns to accommodate the new network topology. Budding networks take longer to solve the trade-off problem of pests versus water shortages, but in the end both networks achieve similar results. The slightly greater productive efficiency of the budding network at the end of the simulations is not statistically significant; it is probably due to ongoing perturbations to the evolving network which force that network to explore cropping patterns that better fit local conditions.

The similarity in long-term productivity of a budding network versus the full network is supported by a statistical analysis of the effect of three ecological parameters and three social parameters on two dependent variables: harvest per unit area and number of synchronized *subak* clusters. The results of a linear regression model are shown in Table 3. The 'number of synchronized clusters' is a count of the number of adjacent *subaks* that share the same cropping pattern. It can vary from one (when all *subaks* share the same cropping pattern) to fourteen (when each *subak* uses a different cropping pattern). These clusters determine the behavior of the network. *Subaks* can control the dissemination of pests between fields by synchronizing cropping schedules, thereby decreasing the number of *subak* clusters. Alternatively, increasing the number

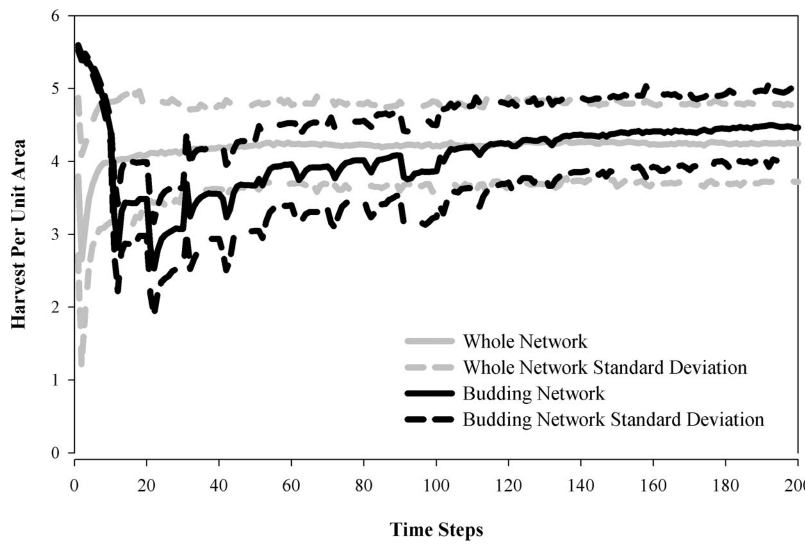

Figure 9 Average harvests over 100 simulations for two different networks: the whole network from the start and the evolving network with new *subaks* added every ten years.

Table 3 Regression model of the output of the simulation model

	A. Number of subak clusters		*B. Harvest per unit area*	
Independent variables	*Standardized coefficient*	*P*	*Standardized coefficient*	*P*
Budding Ttime	0.033	0.044	−0.005	0.380
Pest diffusion Rate	−0.292	0.000	−0.987	0.000
Pest growth rate	−0.081	0.000	−0.272	0.000
Water input	−0.035	0.029	0.018	0.000
Prob. innovation	−0.04	0.013	0.037	0.000
Adopt resistance	0.807	0.000	–	–
Cluster count	–	–	−0.172	0.000
N	972		972	
Adjusted R2	0.745		0.974	
F	473		6045	
P	0		0.000	

of clusters reduces water stress. As expected, pest growth and diffusion rates are negatively correlated with the number of *subak* clusters. Water input and the probability of innovation correlates with the number of clusters, although not as significantly as pests (Table 3$$$A). Budding time is the least significant independent variable. The number of *subak* clusters is analyzed as the dependent variable because the structure of *subak* clusters is dynamic, determined by the system's state at *t*-1. The number of *subak* clusters is therefore an emergent property of the model. Stated differently, there is no programming in the model that determines the optimal number of *subak* clusters – this property arises as each *subak* explores its local environment.

In regression 3B the number of *subak* clusters is treated as an independent variable. To do this we eliminate the parameter that increases the resistance to adopting a neighbor cropping pattern (because this strongly correlates with the number of clusters). We suggest this as a valid approach because the operation of the complete socio-ecological system is based on complex feedback relationships between the number of *subak* clusters and the balance between water availability and pests. Cluster patterns emerge from decisions taken by each *subak*, and the appearance of different-sized clusters enables the network to cope with the problem of pests. Of the three social factors (decision rules for changing cropping schedules) included in the model, the most important for evaluating the plausibility of the proposed budding model is, of course, the budding time. This analysis shows that budding time has little significant long-term effect on either harvests or the structure of *subak* groups.

It may appear counter-intuitive that the *subak* cluster count has a negative correlation with harvests. This can be explained because the regression model is a linear analysis that cannot easily account for non-linear feedback relationships. A large number of small clusters reduces water stress but encourages the growth of pests. It is not the sheer number of clusters but the overall network structure that improves harvests for all *subaks*.

It is worth noting that 'cooperation' is not merely mimicking one's neighbor *per se*. Depending on the ecological conditions, pro-social behavior can also be expressed by unlinking one's *subak* from a pre-existing cluster of synchronized *subaks* and fragmenting the network. A *subak* may synchronize with one cluster of others for a period of time and then quickly shift to another. The network as a whole consists of a nested hierarchy of different-sized clusters of *subaks*. This is also the structure that we see in the real Pamos Apuh water temple network (Lansing 2006).

The budding process presents a potential challenge to the expansion of a bottom-up rice irrigation system because repeated shocks to the system could potentially push it outside the parameter space where good rice harvests can be sustained. But the computational model presented here suggests that it was possible for networks of *subaks* to expand while sustaining high productivity.

Conclusion

Balinese water temple networks show that complex patterns of cooperation can emerge and persist as a result of feedback in a coupled human-natural system (Lansing et al. 1998). In our budding model, local initiatives and demographic events, rather than elite sponsorship, power the creation of a landscape of complex physical irrigation systems and an equally complex hierarchy of flexible common-pool resource managerial institutions.

For such a process to operate, certain conditions must be met. A combination of evidence ranging in date from the ninth century to the present day indicates that Balinese villagers possessed the technical skill, organizational robustness and cooperative bent required to build such systems. The budding process itself presents a potential challenge to the expansion of a bottom-up rice irrigation system because repeated shocks to the system could potentially push it outside the parameter space where good rice harvests can be sustained, and poor harvests could make further expansion economically unviable. However, the computational model just presented suggests that it may indeed be possible for networks of *subaks* to expand while sustaining high productivity.

While acknowledging that other processes also played roles, we propose that farmer-driven budding was a critical contributor to the expansion of irrigated rice agriculture on Bali in many times and places. Since it occurs at a local level among 'peasant' families and villages that do not have easily differentiated material culture, it would be difficult to distinguish such budding from other community-formation processes using traditional archaeological data. As we have demonstrated, in this and similar cases the use of genetic data may be of great assistance in evaluating hypotheses.

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Note

1 It is said that the first king of Mengwi, together with the lord of Blayu, built a dam in the river Sungi, just west of Blayu' (Schulte Nordholt 1996: 58).

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