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Robustness and Large-Scale Change in Social-Ecological Systems: The Hohokam of the Phoenix Basin

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Abstract

Societies frequently generate public infrastructure and institutional arrangements in order to mediate short-term environmental fluctuations. However, the social and ecological consequences of activities directed at dealing with short-term disturbances may increase the vulnerability of the system to infrequent events or to long-term change in patterns of short-term variability. Exploring this possibility requires the study of long-term, transformational change. The archaeological record provides many examples of long-term change, such as the Hohokam of the Phoenix Basin. The Hohokam occupied the Phoenix Basin for over a thousand years and developed a complex irrigation society. In the 14th century, Hohokam society experienced a reduction in complexity and scale possibly associated with regional climatic events. A framework for exploring robustness in coupled social-ecological systems is briefly presented and applied to the Hohokam Cultural Sequence. The possibility that the success of the Hohokam irrigation system and associated social structure may have increased their vulnerability to rare climactic shocks such as those that occurred in the 14th century will be explored.

Introduction

The ever-increasing scale of the influence of human activity on the biosphere demands that society develop mechanisms to respond to rapidly accelerating anthropogenic change. Specifically, we need to enhance our collective ability to anticipate and respond to the complex consequences of coupled environmental and social change. This is a very difficult task for several reasons, but we suggest that there are two issues of central importance: 1) complex social and environmental changes often play out over long temporal scales and across multiple spatial scales and 2) there is a degree of irreducible uncertainty surrounding these changes.

Many past societies faced similar challenges. The archaeological record provides many examples of societies that underwent large scale transformations possibly as a result of their inability to cope with problems related resource degradation and environmental change. Tainter (1988) suggests that large scale transformations (collapse) may be due to the fact that at some level of social complexity, the costs of further complexification outweigh the benefits. This is a very general principle which allows for a range of different causal mechanisms to induce a large scale transformation. One possibility is that individual agents perform cost benefit analyses associated with their participation in a social system. As the society complexifies, costs may begin to exceed benefits. Agents will become less willing to voluntarily participate or be coerced to participate in a social system. Transaction costs associated with the maintenance of intuitions and organizations then rise, creating instability and promoting the possibility for transformations to occur.

In this paper we explore a more specific relationship between social complexity and transformation related to the way in which societies deal with uncertainty and environmental variability. One clear benefit from being a member of society is the mediation of variation in resource availability. A prominent example is the effect of irrigation systems on water availability in so-called hydraulic societies. However, because humans discount the future, societies may focus their efforts on coping with short-term variability. This short-term focus is problematic for several reasons, but a prominent issue is that resource use strategies often fail to incorporate the full complexity of social ecological interactions, the existence of multiple stable configurations, and threshold behavior. Thus human activity directed at influencing ecological processes that operate on short temporal scales (variation in rainfall) may influence processes that operate on long temporal scales (soil degradation). We may hypothesize that in adapting to short-term variation (a particular disturbance regime), societies may become vulnerable to shifts in the disturbance regime, or to infrequent events. Put another way, in becoming robust to one type of variation, they may become vulnerable to other types of variation and change, setting up the conditions for large scale transformation. This paper explores this "robustness-vulnerability trade-off" hypothesis in the case of the Hohokam.

Robustness, institutions, and change

In order to examine this robustness trade-off as a driver of large scale change, we must first define exactly what is meant by the term robust. We must then link institutional and ecological dynamics to robustness. In this section we define robustness in the context of a coupled social ecological system, and suggest some elements for a analytical framework. The case of the Hohokam is then analyzed based on this framework.

Defining Robustness

The concept of robustness is well developed in engineering where it refers to the maintenance of system performance either when subjected to external, unpredictable perturbations, or when there is uncertainty about the values of internal design parameters (Carlson and Doyle, 2002). Robust design often involves a trade-off between maximum system performance and robustness. A "robust" system will typically not perform as efficiently with respect to a chosen set of criteria than its non-robust counterpart. However, the robust system's performance will not drop of as rapidly as its non-robust counterpart when confronted with external disturbances or internal stresses.

Robustness is a very natural concept for systems that have been designed with specific performance objectives in mind. However, when some component parts of the system are self organizing, such as the ecological component of a social ecological system, the meaning of robustness is not so clear. What is the performance index? Resilience, a similar concept to robustness that has been developed in ecology (Holling, 1973), measures the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures. Resilience is an appealing concept and it is tempting to extend it to Social Ecological Systems (Berkes et al., 1998). However, resilience concepts can be difficult to apply to systems in which some components are consciously designed (Carpenter et al., 2001).

Although it seems natural to extend the idea of robustness to a social-ecological system, it is difficult in practice. In engineered systems, defining a performance index is straight-forward. Engineered systems are frequently relatively simple, controllable, and better understood than ecological or social systems. Even complex engineered systems that are composed of many subsystems, like a jet airplane, have relatively complete blueprints that can be used when diagnosing a problem and engaging in repair. Coupled social ecological systems (SESs) are never fully designed or controllable, nor are they amenable to the definition of one simple, easily measurable performance index such as output value minus input costs. In this sense fully engineered systems and SESs provide examples at different ends of the spectrum of systems with both designed and self-organizing subcomponents and levels of uncertainty. In the former, the majority of subsystems are designed (airplane components), very few subsystems self-organize (pressure drop over an airfoil), and uncertainty is low (mostly eliminated by wind tunnel experiments and prototype testing). In the later, the majority of components are self organizing (ecological systems, social networks), very few are designed (rules of interaction), and uncertainty is high (experimentation is difficult or impossible). It is the nature of such systems with partially designed and partially self organizing subcomponents that may be at the root of large scale transformative change. As society focuses its energy on designed subsystem that address specific ecological processes, it may alter the self organizing dynamics of the ecosystem. This may induce major shifts in ecosystem dynamics (Scheffer et al., 2001) and, in turn, transformational social change.

An analytical framework

Any framework aimed at understanding the interaction between human groups and the environment must recognize three issues: 1) the need to maintain cooperation and potential for collective action within the social system, 2) that ecological systems are dynamic, as are the rules that govern interactions between agents, and 3) ecological systems can occupy multiple stable states and move rapidly between them. The first of these issues has become a well developed field in the last three decades. The conditions under which cooperation is maintained or will evolve has been the focus of field researchers, game theorists and experimental economists for some time (Binmore, 1998; Ostrom and Walker, 1994; S. and H., 2003). However, this work focuses on resource users and their actions when payoffs are constant over time, i.e. the resource base is static. Dynamic or differential game theory allows the incorporation of the second issue into models of strategic interaction. Dynamic games have been applied to dynamic resource management issues (e.g. Clark, 1990; Mäler et al., 2003) but here the focus is to determine optimal strategies and the assessment of the effectiveness of economic instruments toward achieving them. Little attention has been paid to the institutional context; it is simply assumed that the necessary institutional and any other associated infrastructure is in place. Finally, the third issue has been addressed in several recent papers (Carpenter et al., 1999a, 1999b; Scheffer et al., 2001; Anderies et al., 2002; Janssen et al., 2004; Brock and Xapapadeas, 2004). These studies focus on management regimes that reduce the probability that a system with multiple stable states will enter, and possibly remain in, undesirable states. However, these studies do not include institutional contexts.

To adequately address large scale social change driven by ecological and environmental factors, the resource, its users, its governance system, and associated infrastructure must be analyzed as a coupled system. To accomplish this, a conceptual framework developed by Anderies et al (2004) is employed. The "framework" is simply an articulation of the key actors in the system and the nature of the key interactions between them to help guide the analysis of a SES (Figure 1). This representation is based on the fact that a SES is an ecological system intricately linked with and affected by one or more social systems. Specifically, the term SES refers to the subset of all possible social systems in which some of the interdependent relationships among humans are mediated through interacting biophysical and non-human biological units.

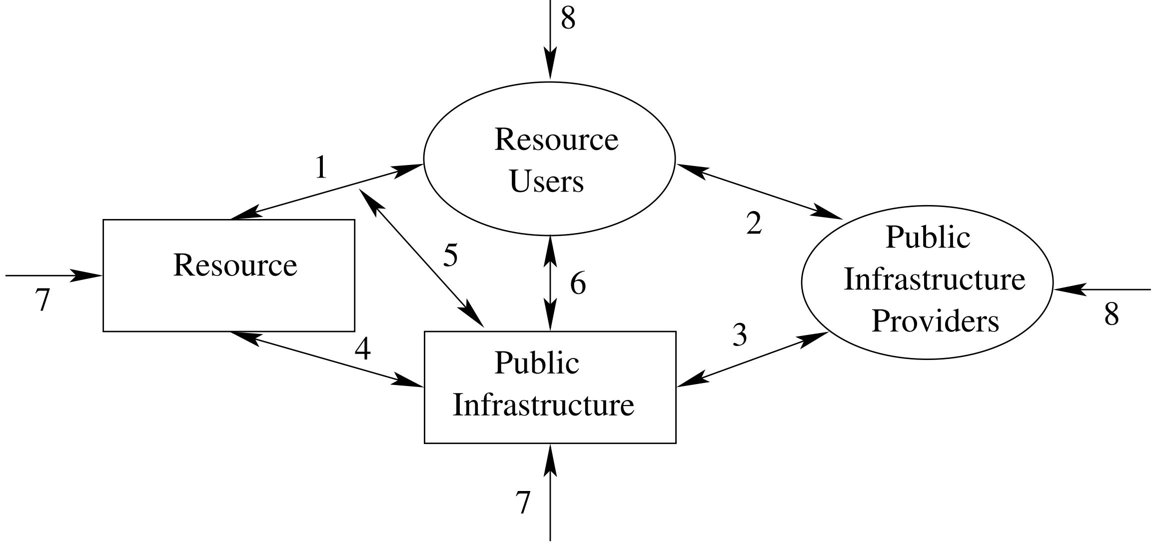

Figure 1: A simple framework that highlights the main components and linkages important to characterizing a SES.

Two components of the SES are composed of humans (ellipses in Figure 1): the resource users and the public infrastructure providers. There may be a substantial overlap of the individuals in these two groups or they may be entirely different individuals depending on the structure of the social system governing and managing the SES. The other two components consist of the resource base itself and public infrastructure. Public infrastructure combines two forms of human-made capital—physical and social. Physical capital includes any engineered works such as dikes, irrigation canals, etc. By social capital we mean the rules actually used by those governing, managing, and using the system and those factors that reduce the transaction costs associated with the monitoring and enforcement of these rules (Ostrom and Ahn, 2003).

In our examination of robustness, we address two types of disturbances. External disturbances include biophysical disruptions (Arrow 7) such as floods, earthquakes, landslides, and climate change which impact the resource and/or the public infrastructure or cultural/socioeconomic changes (Arrow 8) such as population increase, technological/economic change, or ideological/political changes that impact on the resource users and the public infrastructure providers. Internal disturbances refer to rapid reorganization of the ecological or social system induced by the subsystems of the ecological or social systems.

This framework provides a basis for examining the "robustness-vulnerability trade-off" hypothesis in the case of the Hohokam. As we discuss the Hohokam with respect to the linkages depicted in Figure 1, of key importance are strategic interactions between agents within and across the resource user and public infrastructure provider groups and the rules devised to constrain the actions of agents *vis à vis* one another and the resource base (agricultural land and irrigation system). Such interactions may have played important roles in structuring Hohokam society and, in turn, may help understand some aspects of the transformations suggested by the archaeological record.

The Hohokam: Loss of robustness and transformation?

It is believed that roughly 14,000 years ago, the ancestors of American Indians migrated from northeast Asia across the Bering Straits land bridge and arrived in North America. These early settlers were hunter gatherers with a rich array of mega-fauna to hunt. Small groups of nomadic hunter gatherers occupied the American Southwest surviving on game and wild plants. At this point, with low population densities and a relative abundance of natural resources, there was probably no need for complex public infrastructure. However about 3,000 years ago these nomadic groups became more sedentary and adopted agriculture as part of their subsistence strategy. Scarcity of wild resources and game may have caused a reorientation of the relationship between resource users and the resource base (Link 1 in Figure 1). With this reorientation came the redefinition of the resource base from wild and mobile resources to a combination of fixed land resources, river water, and wild resources.

In the early stages of this sedentary period, public infrastructure probably played little role in the relationship between resource users and the resource base (Link 5 non-existent). Referring to Figure 1, only the resource users oval, the resource box, and Link 1 would exist. However, as the population grew and water became more scarce, there may have been a need to manage variation in water availability that resulted from fluctuating rainfall (Arrow 7 in Figure 1). As first suggested by Karl Wittfogel, the need for "hydraulic management" may have heightened the need for public infrastructure and increased social complexity, giving rise to Link 6 in Figure 1). Initially, public infrastructure would consist mainly of irrigation canals and informal institutions required to mobilize labor to maintain them. The physical infrastructure directly impacts the resource base by transforming the way in which it is used (Link 4). As water became ever more scarce, there may have been a need for additional public infrastructure in the form of *formal* institutions (rules) that governed the relationship between the resource users and the resource itself. Such rules would specify when and how much water agents could remove from the system, and when and how much labor agents would have to provide labor for maintenance. The influence of institutions on the relationship between agents and the resource is depicted as Link 5.

In the early stages this complexification process, the role of resource user and public infrastructure provider were probably occupied by the same individuals. However, with increased social complexity, there may have developed opportunities for specialist public infrastructure providers to emerge. These specialists would control the maintenance and construction of physical infrastructure (Link 3) and the actions of resource users (Link 2). The relationships between agents within each of these groups are subject to both endogenous and exogenous drivers such as political, social, and cultural change (Arrow 8). The question of interest here is, can a general description of how the four entities and the links between them depicted in Figure 1 likely evolved in response to managing scarce water resources and associated intergroup conflicts improve our understanding of the major transformations observed in the Hohokam cultural trajectory? It is to this question we now turn our attention.

The context

The context for the Hohokam Cultural Sequence is extremely rich and detailed filling the pages of books, e.g (Andrews and Bostwick, 2000), and articles, e.g. (Bayman, 2001). Only a very rough outline of major events is presented here based on these sources and personal communication with archaeologists specializing in the American southwest. The Hohokam occupied Arizona and Northern Mexico from around A.D. 1 to 1450 (Andrews and Bostwick, 2000). The Hohokam chronology is constructed based primarily on changes in pottery and architectural styles and settlement patterns observed in the archaeological record. The key periods, phases and events for this study are summarized in Table 1.

The chronology shown in Table 1 tells a story of the expansion of irrigated agriculture, the development of pottery production along with a regional trading system in exotic items associated with "ballcourt" settlements. Early in the sequence, in what is called the Pioneer period, the houses were built in pits and the settlements were small and dispersed. The main type of pottery style called "red on buff" developed, and cremation was the dominant burial method. This period witnessed the emergence of a craft economy involving not only the production of red-on-buff ceramic containers, but also fired red-clay figurines, and the fabrication of ornaments with marine shell, minerals, and obsidian. (Bayman, 2001). During the Colonial period that followed, the archaeological record reflects a time of continued expansion but with

Year	Period	Phase	General Characteristics
1540	Historic		Spanish explore southern Arizona. Development of historic Pima and Tohono O'odham (Papago).
1450	Protohistoric (1450-1540)		Hohokam cultural collapse.
1350	Classic (1150-1450)	Polvoron	Pit structures built. Population decline.
1300		Civano	Shift from red on buff to black on red (Salado Polychrome). Big houses constructed. Dissappearance of highly stylized crafts associated with ancestor worship.
1200		Soho	Rectangular platform mounds with compound walls dominate villages. Ballcourt system abandoned. Platform mounds have similar spacing to ball courts, but community centers become more nucleated.
1150			Aboveground residential area with compound walls. Decline in Hohokam interaction outside Gila-Salt river valleys as the overall regional system shrinks.
1125	Sedentary (900-1150)	Santan	Snaketown abandoned. Shift from cremation to inhumation burials with polished red wares.
900		Sacaton	Expansion from the colonial period continues. Mass production of pottery. Use of ballcourts and cremation continues. Maximum extent of regional system reached.
875	Colonial (750-900)	Santa Cruz	Artistic florescence. Elaborate cremation rituals. Courtyard groups with shared ovens emerge. Ballcourt system expands, related to regional exchange networks.
800		Gila Butte	Period of expansion, first ballcourts appear and increased trade in exotic items is evident.
700	Pioneer (1-750)	Snaketown	First capped low platform mounds. Cremation predominant mortuary practice. Red-on-buff pottery.
600		Sweetwater	Irrigation systems continue to expand. Large canal systems appear on the north and south side of Salt River.
500 450		Estrella	Irrigation system expands, large canals appear. Red-on-gray pottery. Bow and arrow used in the Southwest.
300		Vahki	Polished red wares.
50			Irrigation system begins to develop - First canals built.
A.D.1		Red Mountain	Beginning of pottery production. Small, dispersed, permanent villages with emphasis on farming.
B.C.		Late Archaic (1500 B.C. - A.D. 1)	Hunters and gathers with limited agriculture. Clay figurines. Small pithouses. Seasonally occupied hamlets.

Table 1: Overview of the Hohokam cultural sequence. Based on (Bayman, 2001; Andrews and Bostwick, 2000) and K. Kintigh (personal communication).

elements of the "solidification" of Hohokam culture and regional system. Ballcourts emerge, possibly signifying the increased formalization of a regional trading network. More stable settlement patterns emerge in the form of courtyard groups emerge with shared ovens, and there is an elaboration of cremation rituals (along with the associated crafts).

Next in the chronological sequence as a period termed the "Sedentary" in which the major aspects of Hohokam culture remain fairly stable yet expand in scale as evidenced by what was perhaps the mass production of pottery for an expanding regional trading network associated with the ballcourt system (whose distribution closely follows that of red-on-buff pottery (Kintigh, personal communication)). The signatures of this period give the sense of success during which a culture enjoyed material abundance and ideological expansion. The areal extent of this cultural signature, which probably reached its maximum during the Sedentary period, is shown in Figure 2. Within the core area, an impressive irrigation infrastructure developed (Figure 3). However, this period of relative stability and success gave way to the period termed the Classic which saw "unprecedented changes in patterns of settlement, technology, material culture, and ideology.." (Bayman, 2001, p. 281).

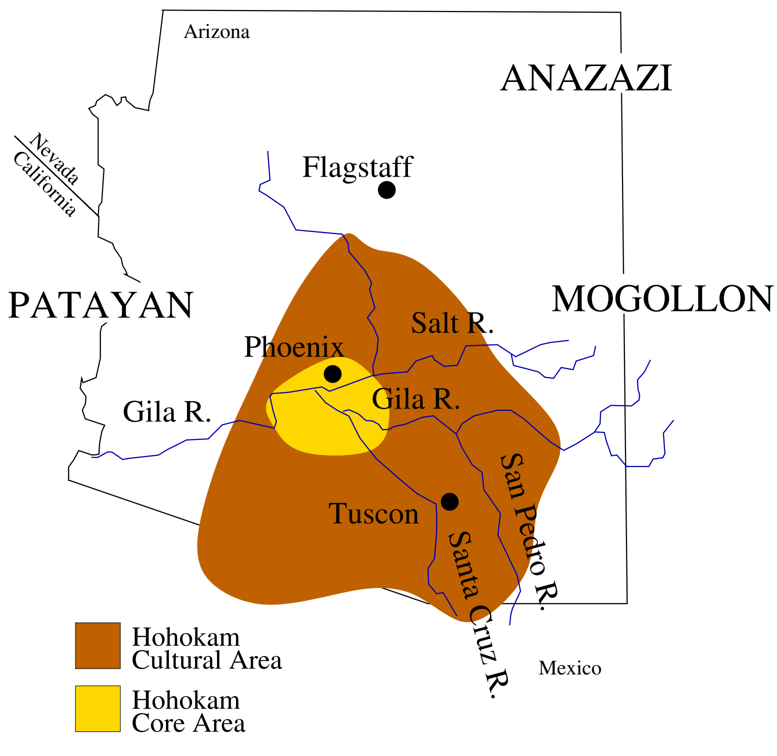

Figure 2: Map of present-day Arizona showing the extent of the Hohokam culture. Adapted from (Andrews and Bostwick, 2000) and Kintigh (personal communication).

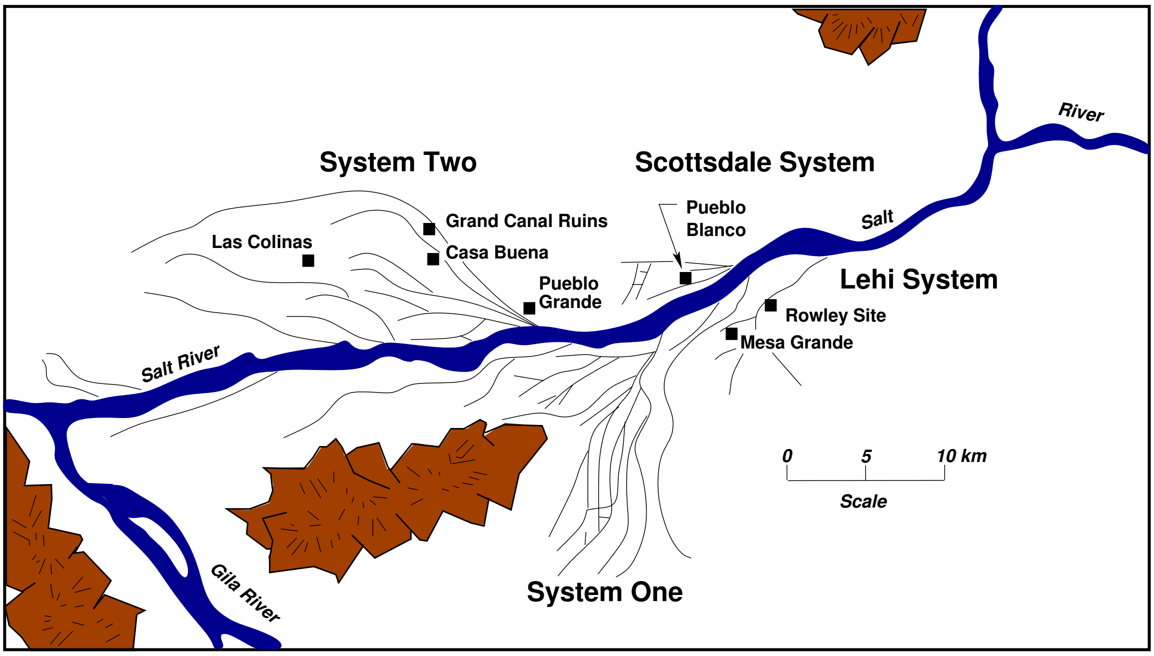

Figure 3: Map showing the extent of a portion of the Hohokam irrigation system. The system covers a large area, on the order of a large portion of the present-day Phoenix metropolitan area. Adapted from (Bayman, 2001) and Kintigh (personal communication).

Transformation

The archaeological record suggests major changes occurred in the Hohokam cultural sequence in the period between A.D. 1150 and 1450. The change was marked by the abandonment of the ballcourt system and a contraction of the regional system. The ball courts were replaced by platform mounds, and the open courtyard, pit house settlements were replaced with above-ground residential areas with compound walls. Community centers become more nucleated. Later in the Classic period, the platform mounds became walled off. At the same time, there is a shift from red-on-buff pottery to black-on-red and a disappearance of highly stylized crafts associated with ancestor worship. Finally, toward the end of the Classic just before the Hohokam cultural collapse, massive structures now called "Great Houses" were built.

Is it possible that these transformations were a response to, at least in part, the need to address resource scarcity issues? If these transformations were related to managing scarce resources and were, in fact, successful at doing so, what precipitated the more abrupt transformation that followed: the cultural collapse of the Hohokam? It is tempting to isolate a single factor that precipitated the "collapse" of the Hohokam such as drought and floods in the 14th century, soil salinization and degradation, canal sedimentation, disease, immigration induced overpopulation, or warfare (Bayman, 2001; Andrews and Bostwick, 2000). However, there is evidence to suggest that none of these factors alone was responsible.

The Hohokam occupied the Salt River Valley for a 1000 years at least. As (Andrews and Bostwick, 2000) surely they would have encountered soil salinization and soil degradation problems long before 1300 and learned how to manage by flushing and fallowing. Similarly, they would certainly have developed means to maintain the canal system and avoid sedimentation. Further, the Hohokam must have endured droughts and floods prior to those in the 14th century. Why should those in the 14th century have such a dramatic impact? If warfare did have a role to play, why and with whom were the Hohokam at war?

The explanation for the collapse of Hohokam Society probably involves a combination of such factors, and in fact may be closely related to its success up to that point. The idea of a robustness-vulnerability trade-off captures both this success and the multiplicity of factors that may have combined to cause Hohokam Society to unravel over a number of generations. The conceptual framework (Figure 1) provides a means to organize these processes.

Institutions and Resources

Consider the changes that occurred in the Classic period in light of Figure 1 and the irrigation system pictured in Figure 3. Although not all the canals were used contemporaneously, this system is quite extensive. If population densities were sufficiently low so that typical annual flows in the Salt River enabled the irrigation of sufficient land area to feed the population most of the time, it is conceivable that the management of this system was possible without large-scale, hierarchical organization. At this point, the linkage between the resource users and the public infrastructure was most likely based on informal rules and norms of behavior. The Hohokam may have been a quite egalitarian, open society as reflected by the open courtyard settlement patterns with communal resources (ovens) and active links with other communities through the ballcourt system. At this stage, resource users and public infrastructure providers are one and the same, so Links 2 and 3 are irrelevant. Link 5, which represents the influence of institutional arrangements on the relationship between users and the resource would have been maintained by the high levels of trust possible in a small, open society.

In these circumstances, the only external threat on the system is from Arrow 7, either as it affects the resource (e.g. drought) or public infrastructure (e.g. flood). However, regardless of the scale of the system, a flood would pose the same threat. The important issue is the availability of excess labor to repair damage. A small system would perhaps have less damage, but supports a smaller population able to repair it. Why would a smaller population be better able to cope with such assaults?

At this point it is important to recognize that the Hohokam did not rely on irrigated agriculture alone. They relied on a host of wild resources harvested from the Sonoran desert which, although very dry, is rich in flora and fauna. It may be that these wild resources played an important role in both the changes witnessed in the Classic period and the eventual Hohokam cultural collapse.

For a small population practicing some irrigated agriculture while harvesting a substantial amount of wild resources, a flood might not pose a great problem. The harvesting of wild resources would be sufficient to carry the population through a period of reduced agricultural harvests and canal repair. In fact, early agriculture may have been a means to dampen the effects of fluctuations in wild resource availability. In this way, the Hohokam may have used a resource portfolio approach to enhance their robustness to fluctuating rainfall patterns. The success of this approach would allow population to grow, putting further pressure on the resource base. At some point, water resources would become stretched and conflict over use would arise.

The predicted outcome from resource scarcity is the development of more clearly defined property rights and more complex institutions to govern resource distribution. Clearer definitions of property rights may be reflected in a stronger demarcation of personal space and a heightened sense of connection to place. More concern about how property is passed from one generation to another would naturally emerge. All of these process are consistent with what is reflected in the changes that took place in the Classic period. Above-ground walled compounds suggest a clearer definition of personal property. More nucleated communities may indicate extended kin groups where relatedness becomes more important due to its implications for the transfer of property across generations. Inhumation replacing cremation might suggest a stronger connection to place, to particular resources in space. Complexification of institutions aimed at addressing local resource scarcity would require energy and resources which would have to pulled from other pursuits. This is consistent with the contraction of the regional system (although this is controversial (Bayman, 2001)) and a reduction in the production of export goods.

This process could be characterized from the perspective of robustness as one in which natural capital (wild resources) was replaced with institutional capital (more complex rules of behavior, more advanced concepts of rights, etc.) to cope with a fluctuating environment. This institutional capital, however, requires significant resource input to maintain. Agents' respect of their rights and duties must be monitored, transgressions sanctioned, and conflicts resolved. Clearly, if this process occurred, it was somewhat successful. After all, the Hohokam had sufficient spare labor to build platform mounds, and reasonably complex dwellings. The important question is exactly how much surplus production was possible and what level of institutional complexity it could maintain.

Even this level of institutional complexification may not require the emergence of a hierarchy - a social system in which resource users and public infrastructure providers are completely separate. It is difficult to know whether a hierarchy emerges as a matter of necessity whereby some resource users reluctantly accept responsibility to provide public infrastructure, or as a result of opportunists who exploit the existence of surpluses (Olson, 1982). Regardless of the mechanism, the emergence of a separate group of public infrastructure providers adds new opportunities and problems to the system. Links 2 and 3 in Figure 1 now become important. It may be that task specialization enhances the efficiency with which public infrastructure can be developed and maintained (Link 3). However, the system is now open to a new range of potential disturbances (Arrow 8). High levels of trust and shared norms and behaviors keep the costs of monitoring, sanctioning, and conflict resolution low. Specialization of tasks introduces new incentives to both resource users and public infrastructure providers. Public infrastructure providers may have a strong incentive to shirk - to not carry out their duties of monitoring, sanctioning, coordination, and conflict resolution. They may not invest resources in the maintenance of the public infrastructure. This adds a new type of collective action problem: who monitors the performance of the public infrastructure providers? Further, lack of confidence in the public infrastructure providers may provide an incentive for resource users to shirk their duties - i.e. to break the rules. When agents begin to behave this way, Arrow 8 become very important.

Again, there are signatures toward the end of the Classic period the may be consistent with such collective action problems. The key features potentially associated with the coordination of the canal system are the platform mounds. Figure 2 shows the location of some of the major mounds in the Salt River Valley. There were many more than those shown, at least 50 mounds, regularly spaced at 5km intervals. It has been suggested that these mounds were tied to the organization and operation of the canal system. It is difficult, based only on the archaeological record, to infer the role these platform mounds may have played, but the fact they are walled is interesting. Is this evidence that elites (public infrastructure providers) were attempting to sequester themselves from resource users? Also interesting is the construction of "Great Houses" near the end of the Classic. These structures could be evidence that less of the surplus generated by irrigated agriculture was being reinvesting in maintaining productive public infrastructure, being instead siphoned off by the elites. This would weaken Link 2.

The story of Hohokam transformation in the Classic period and subsequent collapse may thus be a story of the evolution of feedbacks between wild resources, irrigated agriculture and institutional change. The initial success of irrigated agriculture in augmenting wild resources allows population growth. This growth puts further pressure on the wild resource base, causing it to degrade. This degradation induces society to shift its focus to developing public infrastructure to enhance the productivity of irrigated agriculture. This process introduces fragilities into the system by introducing Links 2 and 3 and weakening Link 6. The resulting social ecological system is very robust to short term fluctuations in rainfall. However, because Links 2 and 3 are so sensitive to collective action problems, the system is less able to respond to crisis situations when resource users must be willing to cooperate with public infrastructure providers. Further, the degradation of the wild resources that initially drove the development of public infrastructure and increased focus on irrigation eliminated a buffering mechanism against very wet periods - i.e. floods. Thus, by enhancing robustness to short-term fluctuations in rainfall, the Hohokam may have become more vulnerable to infrequent crises such as floods.

Concluding thoughts

This paper presented a simple framework for thinking about the robustness of SESs from an institutional perspective and applied it to the Hohokam Cultural Sequence. Given the nature of archaeological data, this exercise is necessarily very speculative. Further, it may not uncover any new facts about the Hohokam. However, it does focus our attention on a set of interlinked processes that, taken together, engender change. Change occurs when SESs become vulnerable. This vulnerability may come at the expense of enhanced robustness in another domain. By carefully examining the nature of the linkages shown in Figure 1 for a particular system, the trade-off between robustness in one domain and vulnerabilities in another may become more clear.

Our focus on an archaeological example is based on recognizing the importance of the *longue durée* (Redman and Kinzig, 2003) in understanding the dynamics of SESs. Are there regularities in the way societies organize around change, uncertainty, and environmental variability? Is it possible to characterize robustness-vulnerability trade-offs *vis à vis* social and ecological complexity? By the same token, can looking at archaeological cases from an institutional perspective enhance our understanding of them? Can we see signatures of changing institutional arrangements, beyond general "complexification". For example, can we see the manifestation of property rights, and the strategic interaction between agents? What kinds of archaeological investigation and evidence would be required to address such questions? Further research in this area must involve the development of simple models to assess the relative importance of the different factors discussed herein. These models must then be challenged by existing data. Through an iterative process of model and data refinement, it may be possible to characterize some basic principles concerning the evolution of SESs and the trade-offs between robustness and vulnerability it different domains that they may face. These principles could help guide present-day policy development with regard to environmental change.

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