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Robustness, institutions, 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 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 who occupied the Phoenix Basin for over a thousand years and developed a complex irrigation society. In the eleventh and fourteenth centuries, the Hohokam society experienced reductions in complexity and scale possibly associated with regional climatic events. We apply a framework designed to explore robustness in coupled social-ecological systems to the Hohokam Cultural Sequence. Based on this analysis, a stylized formal model is developed to explore the possibility that the success of the Hohokam irrigation system and associated social structure may have increased their vulnerability to rare climactic shocks.

1. Introduction

A fundamental problem faced by human societies is spatial and temporal variability in resource abundance. Different patterns of human social organization and resource use observed historically and in the archaeological record testify to the many ways in which societies have responded to this problem. A society might utilize a portfolio of resources that do not co-vary – i.e. when one is stressed, the other is not. Alternatively society might combine physical and social infrastructure (dams, food storage facilities, redistribution systems, etc.) to buffer resource variability. Either approach, however, requires institutional arrangements to govern resource use and distribution.

Irrigated agriculture is one of the most common means to manage resource variability. It has been suggested that problems associated with operating and

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maintaining irrigation systems has been a major factor in the evolution of complex societies (Wittfogel, 1957). Unfortunately, irrigation systems frequently fail to sustain higher, less variable yields over long periods. The social system underpinned by irrigated agriculture then ‘fails’ in the sense that social complexity declines, physical infrastructure deteriorates, and, in some cases, is completely abandoned. Considerable empirical analysis has been aimed at identifying principles that help distinguish between systems that fail from those that are long-lived (Ostrom, 1990; Webb, 1991; Lam, 1998; Guillet, 1992; Ostrom, 1999). The analysis carried out in this paper is an effort to complement this empirical work.

The management of environmental variation has a close analogy in engineering: robust control. Robust control refers to the maintenance of performance (e.g. the ability to feed a population) when a system is subjected to external perturbations (e.g. highly variable rainfall in space and time). However, as is well known in engineering, a system cannot be robust to arbitrary parameter variations and all classes of disturbances (Balas *et al.*, 1991; Boyd and Barratt, 1991; Gilbert and Kolmanovsky, 1999; Zhou and Doyle, 1998; Carlson and Doyle, 2002). Thus, in developing mechanisms to address an existing suite of environmental disturbances, society *necessarily* becomes vulnerable to other disturbances. This emergent vulnerability is not necessarily a problem as society may choose to enhance robustness to what it perceives as the most important class of disturbances and accept vulnerabilities to others. This weighting process is fundamental to engineering practice, where realistic objectives and design specifications are matched to critical nominal performance (speed, cost) versus robustness trade-offs. Unfortunately, navigating such robustness-vulnerability trade-offs is complicated by the instability of the class of disturbances society faces. Social-ecological systems are typically more complex than engineered systems and can exhibit unexpected and catastrophic changes in behavior (Scheffer *et al.*, 2001). Actions directed at enhancing robustness to a particular class of disturbances may induce changes in ecological dynamics that may, in turn, drastically alter the entire suite of disturbances society faces.

To what extent can shifting vulnerability over time, induced by attempts to reduce temporal variation in food supply, help explain observed, large-scale transformations in social organization and resource use patterns (e.g. the ‘collapse’ of irrigation systems and societies)? Can a better understanding of this process uncover characteristics of institutions that enhance capacity to respond to anthropogenic change? Addressing these questions requires the study of examples of human environment interactions exhibiting changing patterns of resource use and social organization over time. The example that motivates this study, the Hohokam Cultural Sequence in the Phoenix basin, is characterized by more than a millennium of increasing social complexity followed by a relatively short period of decline. With increasing social complexity, resource use patterns shifted from wild resources to intensive irrigated agriculture. When social complexity was decreasing, irrigation-related infrastructure was abandoned. In this paper we combine a qualitative analysis of the Hohokam Cultural Sequence and a simple dynamic model of renewable resource use to address the two questions posed above.

2. Institutions, economic performance, and the Hohokam cultural sequence

Institutions shape economic interactions and performance which, in turn, engender institutional change. The dynamic feedbacks between ecological, economic, and institutional factors drive the development of social-ecological systems over time. Several questions such as why societies evolve along distinct trajectories, why societies often fail to adopt the institutional structure of more successful ones (Greif, 1998), and why inferior institutions persist (North, 1990) have arisen in economics regarding this dynamic process. Historical examples of different economic and institutional arrangements have provided an important source of information regarding these questions (North and Thomas, 1973; Greif *et al.*, 1994; Greif, 1997, 2005). The work reported here is quite similar in spirit but relies on an archaeological rather than an historical case.

Three perspectives concerning institutions, social organization and economic performance have developed in the literature. Two treat institutions as rules that constrain human action imposed from the top down. These two differ in their assumptions about the intent of institutions. One suggests institutions promote efficiency, and changes in relative prices create incentives to construct more efficient institutions (North and Thomas, 1973). The other asserts that institutions are not created with efficiency in mind but, rather, are determined politically to benefit special interests (North, 1981; Magee *et al.*, 1989; North, 1990; Grossman and Helpman, 2001, 2002). Institutions may thus be politically efficient (Magee *et al.*, 1989), but economically inefficient. For a given institutional structure, organizations then emerge that minimize transaction costs (Coase, 1937). The Hohokam ball-court infrastructure and related ritual practice described below could have reduced transaction costs associated with regional trade and promoted specialization in pottery and irrigated agriculture. Similarly, the platform mound infrastructure and related social organization described below could have promoted joint resource mobilization and labor coordination to build, operate, and maintain massive irrigation infrastructure. An interesting question, with implications for the robustness/vulnerability characteristics of the system, is whether these various institutions resulted from efficiency-improving or political incentives.

The third perspective considers institutions at the individual level, focusing on the problem of enforcement (Greif, 2005). An institutions-as-rules approach ignores the second-order collective action problem of enforcing the enforcers (Ostrom, 1990; Ostrom and Walker, 1994). Strategic behavior is central to the analysis of what motivates agents to follow rules and game theory is a natural approach (Ostrom and Walker, 1994; Greif *et al.*, 1994; Greif, 2005). The important point is that institutions emerge from underlying dynamic interactions between agents and thus have potential problems with stability and maintenance over time.

Two institutional issues are especially important for robustness/vulnerability trade-offs: (1) By improving economic performance, better institutions may enhance the extractive capacity of a group and thus generate vulnerabilities related to resource over-exploitation, and (2) Although better institutions may enhance economic performance and reduce vulnerability to resource fluctuations, the problems of strategic interaction may generate new vulnerabilities. Effective institutions require many self-enforcing informal rules and norms which can be destabilized by a variety of perturbations. In this case, vulnerabilities may simply be shifted from ecological to social domains. We combine these ideas from historical institutional analysis with robust control and a simple model of renewable resource exploitation to improve our understanding of large-scale transformations in the Hohokam Cultural Sequence and how similar challenges might be addressed by modern societies.

The archaeological record provides a characterization of general patterns of social organization and resource use over time in the Hohokam Cultural Sequence. Changes in use patterns of two key renewable resources, wild/extensive and irrigated/intensive, and the attendant changes in social organization provide the basis for the formal mathematical model. Table 1 summarizes Hohokam social organization over time. This chronology (period names and dates) originated with the work of Gladwin *et al.* (1937) and was subsequently refined by decades of archaeological research (Bayman, 2001). The details recounted here are based on Bayman's (2001) synthesis of Hohokam Archaeology and work focusing on decline in the Classic period collected in Abbott (2003a).

From 1500 BC to AD 1, the ancestors of the Hohokam relied on small-scale irrigation during the growing season and hunting and gathering at other times of the year. As the population increased, the first hallmarks of Hohokam culture began to appear: pottery production, permanently occupied villages, and cremation mortuary practices. By AD 750, multi-village irrigation cooperatives were established. A growing network of ball courts (oval shaped courts roughly $75' \times 150'$ surrounded by $3'$ berms) and the movement of specialized goods on the landscape provide evidence for social complexification during the Colonial period (AD 750–900). Some suggest that these ball courts were analogous to Mesoamerican counterparts in which ritual ball games took place (Haury, 1976). Their uniform distribution likely expresses uninterrupted connections between communities across a large region (Abbott *et al.*, 2003) (the light gray area shown in Figure 1). Linked by shared beliefs associated with ball-court ceremonialism, these communities potentially formed a 'highly organized and

Table 1. Summary of Hohokam social organization over time

Period	General characteristics
1500 BC–AD 1	Hunter gatherers with limited agriculture. Small pit house settlements and seasonally occupied hamlets were typical. Small-scale irrigation begins.
Pioneer (1–750)	Larger-scale irrigation systems begin to develop. Bow and arrow begins to be used in the Southwest. Irrigation systems continue to expand and multi-village canal systems appear on the north and south side of Salt River. Courtyard groups appear.
Colonial (750–900)	Period of expansion, first ball courts appear and increased trade in exotic items is evident. Artistic florescence follows accompanied by elaborate cremation rituals. Colonial Courtyard groups with shared ovens emerge. Ball-court system expands, related to regional exchange networks.
Sedentary (900–1150)	Expansion from the colonial period continues. Mass production of pottery. Use of ball courts continues. Maximum extent of regional system reached.
Classic (1150–1450)	Above ground residential areas with compound walls emerge. Hohokam interaction outside Gila-Salt river valleys declines as the overall regional system shrinks. Rectangular platform mounds with compound walls dominate villages. Ball-court system is abandoned and community centers become more nucleated. Highly stylized crafts associated with ancestor worship disappear. Hohokam culture collapses around 1450.

Sources: Based on Bayman (2001) Abbott (2003a), and Abbott (personal communication). For further details on the development and refinement of the Hohokam Chronology, see Dean (1991), Deaver (1997), Eighmy and McGuire (1988), and Schiffer (1986).

integrated socioeconomic system' (Doyel, 1981, cited in Abbott *et al.*, 2003). The orientation of the courts has led researchers to speculate that ball-court festivities occurred on a predictable schedule, allowing people from distant communities to time their arrival to participate in ritually sanctioned exchanges of goods (Wilcox and Sternberg, 1983). Recent results concerning the production and movement of ceramics imply frequent, regular, and large volume exchange associated with ball game festivities (Abbott, 2003b). Ball-court ritualism and the associated social structure can thus be viewed as a sophisticated institutional arrangement that enhanced productivity through facilitating task specialization and exchange of various natural resources, agricultural yields, and manufactured commodities in a regional-scale economy.

The institutional–technological system associated with ball courts reached its maximal extent during the Sedentary period (Table 1 and Figure 1). The ensuing Classic period was characterized by 'unprecedented changes in patterns of settlement, technology, material culture, and ideology . . .' (Bayman, 2001). The ball-court network and open pit house settlements were replaced by nucleated

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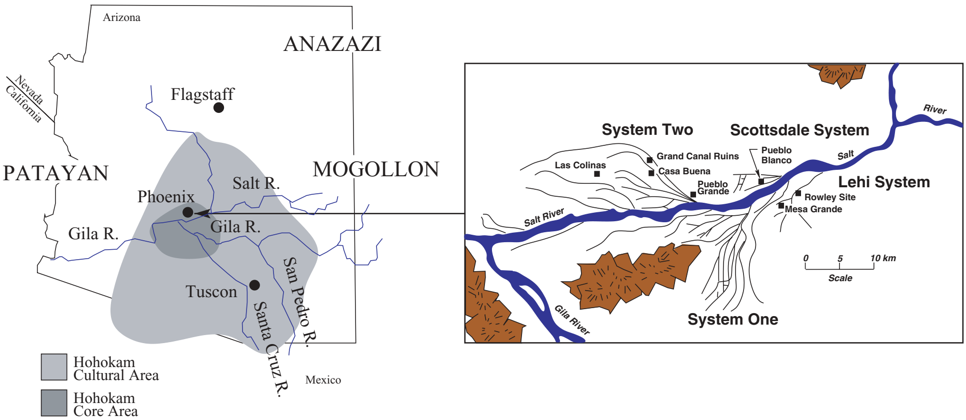
Figure 1. (A): Map of present-day Arizona showing the extent of Hohokam culture. (B): A portion of the Hohokam irrigation system that covers a large portion of the present-day Phoenix metropolitan area.



(A) (B)

Sources: Figure (A) adapted from Andrews and Bostwick (2000). Figure (B) adapted from Abbott (2000) and Bayman (2001).

centers with platform mounds and above-ground residential areas separated by imposing walls. Platform mounds are rectangular earthen mounds roughly 3 meters high, 90 meters long, and 50 meters wide, with steep vertical, well-plastered sides and a nearly level top covered with a smooth layer of adobe. The mound surface supported rooms, courtyards, and other features (Downum and Bostwick, 2003). The mounds were impressive, requiring significant pools of labor to construct. Although there is debate concerning their exact function (e.g. whether they were used for ritual only, were sporadically or permanently occupied and by whom, etc. (Downum and Bostwick, 2003)), it is generally believed that the mounds were used in some way as residences for an elite stratum of Hohokam society.

The mound facilities, with large walls and restrictive access, indicate a narrowing of participation in rituals. Ball courts were likely designed to provide access to a variety of groups, while mounds restricted access to elites, perhaps signifying the emergence of a stratified society. Mound spacing provides some evidence of coordinated management of the irrigated economy. The Classic period associated with the mounds was a long interval of decline with increasingly narrow reliance on irrigation infrastructure, over population, environmental degradation, poor health, and social fragmentation. In the progression from the Sedentary to the Classic, food production technology shifted from primarily extensive, highly variable wild resources to less variable, but more labor-intensive, irrigated agriculture.

Details concerning shifts in production technology and social organization are the subject of academic debate beyond the scope of this paper (but see Abbott *et al.* (2003)). What interests us here is the relationship between these shifts and the robustness/vulnerability characteristics of the Hohokam social-ecological system. What was the sequence of events that led to these shifts? Was it degradation of local subsistence resources stimulating trade and the development of ball courts to regulate it, leading, in turn, to degradation of wild resources at the regional scale, eventually leading to concentration on irrigated agriculture and the development of centralized, complex management and the emergence of hierarchical social organization manifest in platform mound architecture? Or was it success of local subsistence strategies leading to surpluses which allowed production and trade of prestige goods, leading to ball-court ceremonialism which increased the efficiency of trade networks, generating yet greater economic efficiency, eventually leading to the emergence of platform mound elites, more efficient irrigation management and irrigation intensification? A careful analysis based on the robustness/vulnerability trade-offs associated with resource exploitation in a highly variable environment, though not able to distinguish between these possibilities, can help understand how such a sequence of events could have culminated in the 'collapse' of the Hohokam Cultural Sequence at the end of the Classic period.

Both extensive and intensive resource use patterns can reduce the effects of environmental variation on food production by extending the spatial scale at which resources are captured (via trade networks and river networks, respectively). Consider a population that requires both protein rich and carbohydrate rich foods. Irrigated agriculture based on corn, beans, and squash provides carbohydrates and some protein. Wild resources, including game and plant-matter, provide a more concentrated protein source. At low population densities (e.g. in the pre-Pioneer period), the wild resource base could provide sufficient quantities of both resource types. With population expansion, however, although needs can be met most of the time with wild resources, subsistence may become more sensitive to local variation in resource abundance.

Higher population densities may degrade local wild resources, increasing the attractiveness of irrigation. Local resource shortages might be accommodated by shifting emphasis from irrigation to wild resources in wet periods and *vice versa* or through trade. Evidence of major migration from river valleys to drier uplands, perhaps facilitated by abnormally wet conditions, during the Colonial period is consistent with both strategies. The archaeological record also reflects continued expansion and 'solidification' of the Hohokam culture with the formalization of the regional trading network as described above. During this period, the use of both resource types was likely intensifying and there may have been extensive trade between the wild and irrigated resource sectors.

This strategy, enabling more efficient use of resources over a larger area, would enable continued population expansion. Task specialization would be a natural outgrowth associated with larger populations with access to trading networks. Again, the archaeological record is consistent with such a progression of events. During the Sedentary period, major aspects of Hohokam culture expand in scale as evidenced by what was perhaps the mass production of pottery in the Hohokam core area (dark gray region, Figure 1(A)). The signatures of this period are material abundance and ideological expansion that eventually covered one third of present-day Arizona (light gray region, Figure 1(A)). Within the core area, an impressive irrigation infrastructure developed (Figure 1(B)).

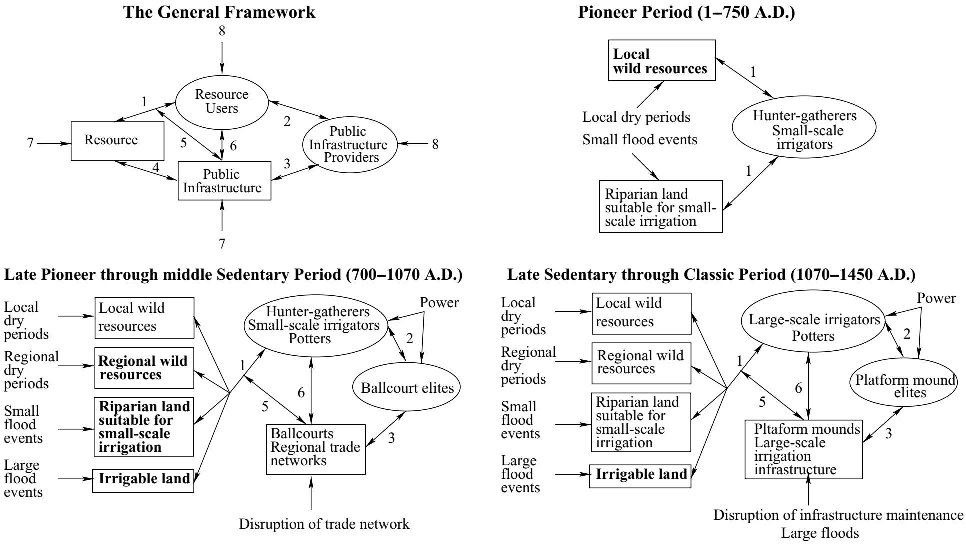
This regional-scale social–ecological system may have suffered from its own success. Continued population growth likely led to further concentration and intensification of riparian and irrigated agriculture in the most suitable areas. The ball-court system may have played an increasingly important role in mediating the exchange of outputs from different resource types as they became more spatially distinct. It seems that, in the Sedentary period, the maximal extent of food production from wild resources may have been reached, so that the use of both types of resources was no longer expanding. Crossing this threshold may have been related to the shift from the extensive ball-court system to the intensive platform mound system in the Colonial period.

This shift in social organization and resource use patterns clearly changed the suite of risks faced by the Hohokam. At each point in time, they may have responded to a range of pressures that forced them into a certain development trajectory. The formal mathematical model developed in the next section is used to explore in more detail whether and how these shifting vulnerabilities may have played a role in the Hohokam cultural collapse.

3. A simple model of renewable resource exploitation

To aid in the development and exposition of the mathematical model, we first perform a qualitative analysis of the robustness–vulnerability trade-offs the Hohokam may have faced using a conceptual framework proposed by Anderies *et al.* (2004). This framework emphasizes the dynamic interaction among four components (top left, Figure 2) in social-ecological systems (SESs): resource users, resources, public infrastructure providers, and public infrastructure. Two components are composed of humans (ellipses in Figure 2): resource users and public infrastructure providers. These groups may be distinct or overlap considerably depending on the structure of the social system. The other two components consist of the resource base and public infrastructure. Public infrastructure combines two forms of human-made capital – physical and social. Social capital refers to the rules used by those governing and using resources and those factors that reduce transaction costs associated with monitoring and enforcement of these rules (Ostrom and Ahn, 2003). The links between elements are numbered for future reference and arrows 7 and 8 represent environmental and social disturbances, respectively.

Figure 2. The general framework (Anderies *et al.*, 2004) applied to the Hohokam Cultural Sequence. The framework makes key interactions between fundamental components in social ecological systems that are especially important to understanding robustness explicit. The links are numbered following Anderies *et al.* (2004) for reference to the discussion in the text.



The three specific instances of the general framework pictured in Figure 2 summarize the sequence of social–ecological configurations that may have occurred through the Hohokam Cultural Sequence. In each figure, labels in bold, bold-gray, and plain text refer to resources of primary, intermediate, and low importance. In the pre-Pioneer period, there was probably little need for public infrastructure. The most important elements would have consisted of the resource users, local wild resources, and riparian land. The most important disturbances were environmental and are listed for each resource type. Food output from wild resources is vulnerable to local drought. Food output from riparian agriculture is less susceptible to drought but more susceptible to flooding. A portfolio composed of these two resources would be fairly robust to short-term fluctuations in rainfall as a result of their 'orthogonality' in risk space; each resource is robust to shocks that do not typically occur simultaneously.

In the Pioneer, Colonial, and early Sedentary periods as the resource portfolio progressively expands, public infrastructure and those that provide it, the ball-court elites, began to play a role. Ball-court elites affected the relationship between the users and the resource base (link 5) through the trade network and ball-court system. Link 6 is introduced because someone must have constructed and maintained the ball courts. A link between resource users and public infrastructure providers became important because their roles became more

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distinct and power relationships may have emerged. The resulting SES was now more robust to local dry periods because it operated at a larger spatial scale. It was more robust to small flood events because more developed public infrastructure allows for irrigation of land further away from flood plain areas. However, the system may have become vulnerable in several ways. It possibly became more vulnerable to regional dry periods and large floods (climatic events that occur on larger spatial and temporal scales). It perhaps also became more vulnerable to social disturbances such as disruptions in trade networks due to disputes or internal conflict. The idea of conservation of robustness becomes apparent – society can only shift vulnerability across scales or domains, but cannot eliminate it.

In the late Sedentary and Classic periods emphasis shifted toward irrigated agriculture, platform-mounds and large-scale irrigation infrastructure. The system contracted as emphasis shifted away from regional-scale wild resources. The system probably became extremely robust to local climate variation. However, irrigation infrastructure may have been more costly to maintain than ball-court infrastructure and is sensitive to large floods. A larger population would now have relied on a more concentrated resource base with no adequate alternative should the irrigation system fail. Failures of large-scale infrastructure require extended periods of concentrated effort to repair, reducing the ability of the system to rapidly recover. Finally, additional institutional and social infrastructure, both subject to disruptions, is required to coordinate irrigation activities and system maintenance.

The application of the framework provides a mechanism to organize key structures in the Hohokam SES across different periods and highlight key vulnerabilities. However, it does not provide a detailed characterization of the relationships between population, capitalization, resource use patterns, vulnerabilities, and potential transformations within the SES. A formal mathematical representation of the system shown in Figure 2 allows us to extend and refine the qualitative analysis.

The reader should bear in mind that the model is not intended to capture specific features of the Hohokam system but, rather, the overall themes relevant in structuring the Hohokam Cultural Sequence. The need for a sufficiently long temporal sequence to observe shifting vulnerabilities and large-scale change motivates our focus on an archaeological case such as the Hohokam, not the details of the case itself. Further, institutions are not formalized explicitly in the model; their role is implicit. For each biophysical configuration analyzed, institutions structure the suite of associated costs, benefits, vulnerabilities, and social interactions that generate the possible dynamical behaviors of the system. The formal model provides the link between institutional configurations (specified in qualitative terms) and social-ecological dynamics (specified in quantitative terms).

The model structure is motivated by representative-agent, bioeconomic models of renewable resource use (Anderies, 1998, 2003; Brander and Taylor, 1998;

Janssen and Scheffer, 2004). The qualitative analysis of the system suggests two main renewable resource types are essential: extensive (type 1) and intensive (type 2). The states of the extensive and intensive resources are measured in terms of harvestable biomass and soil fertility (Anderies, 1998, 2003), respectively. Society produces two types of output: protein rich (type 1) and carbohydrate rich (type 2). Although both can be produced from either resource type, wild resources may have higher productivity of type 1 output and irrigated agriculture may have higher productivity of type 2 output. To determine the resource mix to produce, we assume that society attempts to meet its basic needs with minimum labor (i.e. individuals prefer leisure to additional food beyond basic needs). Note that 'basic needs' is not equivalent to subsistence needs. Basic needs may include food for gifts, rituals, trade, etc.

The mathematical representation of the system is simply a description of the natural regeneration of and labor allocation to each resource type. Resource dynamics are modeled using differential equations describing the state of type 1 and 2 resources, x_1, and x_2, respectively:

$$\frac{dx_1}{dt} = r_1(R)x_1(1 - \alpha_1(R)x_1) - \alpha_{11}Y_{11} - \alpha_{12}Y_{12} \tag{1}$$

$$\frac{dx_2}{dt} = r_2(S)x_2(1 - \alpha_2 x_2) - \alpha_{21}Y_{21} - \alpha_{22}Y_{22}. \tag{2}$$

The term $r_1(R)$, which depends on rainfall, R, is the intrinsic regeneration rate of the wild resource stock. Unexploited wild resource stocks will increase to a rainfall-dependent carrying capacity, $1/\alpha_1(R)$. The subscript j takes on values of 1 or 2 representing output type (protein rich = 1, carbohydrate rich = 2). The subscript i takes on values of 1 or 2 representing resource type (extensive (wild) = 1, intensive (irrigation) = 2). Thus, Y_{ij} represents output type j from resource type i and α_{ij} the impact on resource type i of producing output type j.

As is typical with bioeconomic models, we assume wild resources regenerate logistically. The regeneration rate of irrigated agricultural soil productivity is denoted by $r_2(S)$, where S denotes stream water added to the soil via irrigation activities. The soil regeneration rate depends on S because irrigation water carries nutrients. Maximum soil fertility, $1/\alpha_2$, depends on physical soil characteristics and soil biota.

Environmental disturbance enters through R and S. Fluctuations in rainfall affect the wild resource growth rate and carrying capacity. Variation in stream flow affects soil fertility and agricultural productivity. Rather than explicitly including stochasticity and drastically complicating the analysis, equations (1) and (2) are used to represent *average* conditions (i.e. R and S are constants), and stochasticity is represented as perturbations from average conditions. The objective of the analysis is to identify possible long-run dynamics (steady states) and the sizes of perturbations necessary to cause trajectories to shift between them. Shifts between these steady states represent changes in social organization, institutions, and resource use patterns resulting from environmental disturbances and change.

For clarity, we assume a linear production structure. Lower- and upper-case letters represent *per capita* and total quantities, respectively ($Y_{11} = hy_{11}$ where h is the total population size). Thus we have $y_{1j} = A_{1j}x_1 l_{1j}$ and $y_{2j} = A_{2j}x_2 l_2 K$, where l_{1j} is the labor devoted to producing output j from resource 1 and l_2 is the labor devoted to resource 2. We do not make a distinction between labor directed at producing different types of output from resource 2 – output comes in a fixed ratio determined by A_{2j}. Output from irrigated agricultural activity also depends on capital, K, which includes physical, social, and institutional infrastructure. Each representative agent chooses l_{1j} and l_2 to meet her minimum needs, $y_{1\min}$ and $y_{2\min}$, while minimizing total labor. The formal problem statement is

$$\text{Min } l_{11} + l_{12} + l_2 \tag{3}$$

$$\text{Subject to: } y_{11} + y_{21} \geq y_{1\,\min} \tag{4}$$

$$y_{12} + y_{22} \geq y_{2\,\min} \tag{5}$$

$$l_{11} + l_{12} + l_2 \leq l_{\max} \tag{6}$$

which yields the following optimal labor allocation rule. Define l_2 as

$$\bar{l}_2 = \min\{1/A_{21}x_2K, 1/A_{22}x_2K\}. \tag{7}$$

Then if

$$1 - \frac{x_2K}{x_1}\left(\frac{A_{21}}{A_{11}} + \frac{A_{22}}{A_{12}}\right) > 0, \tag{8}$$

$l_2 = 0$, otherwise $l_2 = \bar{l}_2$. Expression (8) describes optimal labor allocation based on the state of the system (x_1, x_2) and technological constraints (K and A_{ij}). Once l_2 is known, each Y_{ij}, which jointly determine the ecological dynamics, can be computed.

Equation (8) makes the conditions favoring a switch to irrigated agriculture clear: once the left-hand side of equation (8) becomes negative, society devotes some labor to irrigation. This becomes more likely as K increases (obviously), as the wild resource becomes degraded relative to irrigated agriculture (the ratio x_2/x_1 increases), or the productivity of labor in irrigation is higher than in the wild resource.

The model provides a preliminary formalization of the relationships among capitalization, population, and resource utilization. Population and capital stocks are treated as parameters and their effect on resource use decisions and resource dynamics are explored as they are varied. As such, the reader should bear in mind that the cases treated represent snapshots of a dynamic process. For example, Figures 3(A), (B), and (C) represent snapshots of a continuous progression as population increases from 0 to 12,500 taken at population levels of 5,000, 10,000, and 12,500, respectively. Similarly, conditions and events in

Figure 3. Phase plane analysis of the model when K/h=0.01. The curves with arrows show possible trajectories for different initial conditions. The arrows show the direction of flow over time. The population increases from (A) to (C).

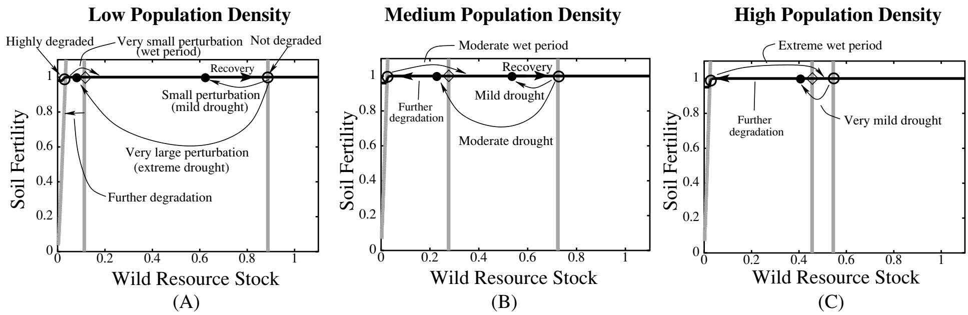


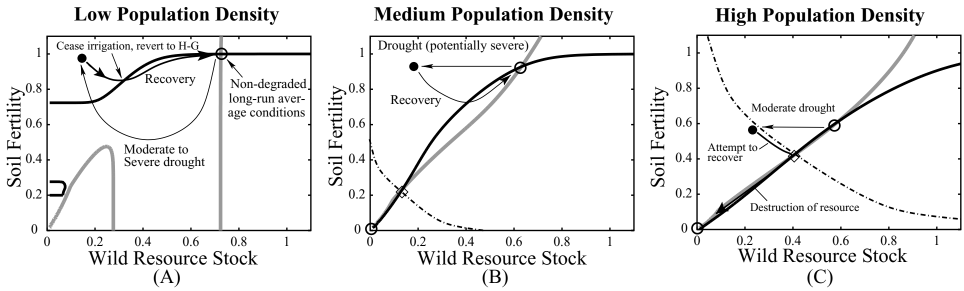
Figure 3(C) may cause the system to move to the configuration in Figure 4(A), and so on. Given that population size and the capital stock are likely correlated, we assume a constant capital–labor ratio and look at three ratios: low, medium, and high. Many of the other parameters in the model (see Table 2) simply scale the units of measurement, and are chosen to simplify our analysis. The basic model results are robust to a wide range of parameter choices.

The choices of α_{ij} will determine the value of h and K at which shifts in model behavior occur. For the choices in Table 2, the basic model dynamics occur over the range $h \in [0,2.5]$. If α_{ij} were chosen an order of magnitude smaller, this range would be [0,25], etc. Equivalently, depending on the units for α_{ij}, each population 'unit' might be 1, 100, 500, 10,000, etc. The population levels used in the following analysis were chosen to roughly coincide with archaeological estimates, which suggest a population unit in the 10,000 range so that $h = 2.5$ means the

Table 2. Summary of variable definitions, parameter definitions, and default parameter values used in the analysis.

Variables		
Symbol	Definition	
x_1	Biomass of wild resource base	
x_2	Soil fertility of irrigated land	
Parameters		
Symbol	Definition	Default Value
r_1	Intrinsic regeneration rate of resource 1	1
r_2	Intrinsic regeneration rate of resource 1	1
l_{max}	Total available labor per individual (e.g. 20 hrs/day)	20
A_{ij}	Output type j per unit labor in resource i	1 for all i and j
α_{ij}	Impact on resource i of producing j	0.1 for all i and j
α_i	Carrying capacity of resource i	1 for i=1,2

Figure 4. Phase plane analysis of the model when K/h=0.2. The curves with arrows show possible trajectories for different initial conditions. The arrows show the direction of movement over time. The population increases from (A) to (C).



population is 25,000. The growth rates of both resource types are assumed to be 1 as are the productivities in harvesting wild resources and generating output in irrigated agriculture.

We begin the analysis for a society with a low capital labor ratio, $K/h = 0.01$ (e.g. small-scale irrigation in riparian areas). The bold lines in Figure 3(A–C) show the values for x_1 and x_2 at which their derivatives are zero–i.e. the variables are not changing (the so-called isoclines). The gray and black lines correspond to wild resource biomass and soil fertility, respectively. Where these lines intersect, neither variable is changing and the system is in equilibrium. There are two stable equilibria (open circles) separated by an unstable equilibrium (diamond). The system will tend toward one of the stable equilibria depending on the initial conditions and will move away from the unstable equilibrium. Figure 3(A) illustrates the social-ecological configurations for a low population density (5000 people). In the stable equilibrium with the wild resource stock at around 0.88, society meets all of its needs using the wild resource ($x_1 < 1$) and does not use irrigation ($x_2 = 1$, i.e. soil fertility is at carrying capacity).

The smaller black circles show the state of the system after a perturbation in the wild resource stock (e.g. a drought). The arrows show the movement of the state of the system during and after the perturbation. For example a mild drought might reduce the wild resource stock from 0.88 to 0.6 as shown in Figure 3(A). The system will recover, moving toward the stable equilibrium and away from the unstable equilibrium. However, if an extreme drought moves the system to the left of the unstable equilibrium, then the system will move toward the stable equilibrium with the wild resource stock at 0.05 (very degraded) and soil fertility slightly less than 1 (some irrigated agriculture is taking place). In this equilibrium, society cannot meet its minimum needs – only 65% of the minimum requirement of type 1 output is met and no type 2 output is produced. However, note that a small perturbation (a wet phase) can push the system back to the right of the unstable equilibrium, enabling the system to recover to its original state. Given that extreme events are required to push the system into the degraded equilibrium, while only a small event can push it out, the system is very robust to perturbations in the wild resource base. Figure 3(A) may characterize the Pre-Pioneer period.

Figures 3(B) and (C) illustrate how the system changes as population grows. At an intermediate population size (e.g. 10,000), the upper stable equilibrium occurs at a wild resource stock of about 0.73, and the unstable equilibrium is now at about 0.28. A smaller perturbation can now push the system to the left of the unstable equilibrium, after which the system will inevitably become degraded unless a perturbation in the opposite direction, such as an exceptionally wet period, pushes it back. (Figure 3(B)). In the degraded state, society cannot meet minimum requirements of either good. Further, a larger perturbation is now required to push the system back to the right of the unstable equilibrium and enable it to recover. The system has become less robust to local drought conditions. To complicate matters, the size of tolerable perturbations shrinks nonlinearly with population increases (Figure 3(C)). When population increases from 10,000 to 12,500, the tolerable perturbation in the wild resource stock drops by a factor of 4 from about 0.45 to about 0.11. (Figure 3(C)). As society approaches a limit, it can lose robustness very quickly.

Next consider a case with much more investment in infrastructure ($K/h = 0.2$). The possible model behaviors, fundamentally different than in the low capital case, are shown in Figure 4 (A), (B), and (C) for three different population densities (10,000, 15,000, and 24,000 respectively). First note that the system can support more than double the population. Second, at lower population densities the highly degraded equilibrium does not exist – there is only one stable equilibrium. This fundamental difference arises from the height of the hump-shaped curve in the lower left-hand corner of Figure 4(A). In Figure 3(A), this hump extends off the graph leaving only the lower two legs visible – the left-most two, almost vertical lines. Increasing irrigation infrastructure lowers the top of the hump and can push it below the soil fertility isocline (black, horizontal, sigmoidal curve in Figure 4(A)).

The existence of only a single long-run equilibrium has important robustness implications. With a low population, the system can recover from any size (thus is extremely robust to) local drought. Consider a drought that reduces the wild resource stock from the equilibrium level to 0.2 (Figure 4(A)). Society shifts emphasis to irrigated agriculture and the system recovers. This process is depicted in the x_1, x_2 phase space by a trajectory moving down and to the right. The downward movement corresponds to depletion of soil nutrients due to increased irrigation activity. The rightward movement corresponds to the recovery of the wild resource enabled by reduced harvesting. When the recovery trajectory intersects the x_2 isocline (around (0.32,0.85), irrigation ceases and society returns to sole reliance on wild resources. The switch occurs when wild resource biomass recovers to the point that labor required to meet minimum needs are less than for irrigated agriculture.

At low population levels, irrigated agriculture is a temporary recovery mechanism that enhances robustness to local droughts. However, several vulnerabilities begin to emerge. If streamflow is correlated with local drought, then the productivity of irrigated agriculture would also suffer. In terms of the model, reducing stream flow is equivalent to reducing the productivity of irrigation infrastructure (reducing K). Thus, society may experience a rapid shift from the situation depicted in Figure 4(A)) to that in Figure 3(C)), with a relatively high population rapidly degrading the wild resource base. A second emerging vulnerability relates to the value of K itself. The maintenance and operation of infrastructure requires coordination and cooperation. Should a shock to the social system cause coordination and cooperation to breakdown, K may fall relatively rapidly and cause the system to shift from Figure 4(A)) to Figure 3(C)). Finally, irrigation infrastructure is sensitive to floods. If during the recovery phase after a moderate drought period (1–5 years in duration) a flood event occurs and reduces K, a shift from Figure 4(A)) to Figure 3(C)) can occur. The system has become completely robust to local drought, but has become vulnerable to three new types of disturbances.

Another important effect of increasing irrigation infrastructure is the generation of new possible system states. When irrigation infrastructure is low, all possible equilibria occur at positive values of x_1 and x_2. Although one may occur at very low value of x_1, the system can nonetheless recover with the occurrence of an exceptionally wet phase. Society does not have the *capacity* to *destroy* the resource base in this case. Efficiency-enhancing institutional arrangements along with sufficient irrigation infrastructure and labor generate a fundamental shift in the underlying dynamics, providing society the capacity to destroy the resource base (Figure 4(B) and (C) as compared to Figure 4(A)). Rather than a single, stable equilibrium, there are three: two stable (open circles) separated by one unstable equilibrium (diamond). One stable equilibrium occurs at positive values of both x_1 and x_2, while the other occurs at the point (0,0) – i.e. both resources are destroyed. Between these two is an unstable equilibrium through which a curve passes (dash–dot curve in Figures 4(B) and (C)) that separates all system states that eventually move toward one or the other of the two stable attractors. All states above and to the right of this curve will be attracted to the positive equilibrium (desirable), while states below and to the left of this curve will eventually be drawn to (0,0). Note that at intermediate population levels (15,000), the system remains extremely robust to local drought (Figure 4(B)) and irrigation is no longer intermittent ($x_2 < 1$ in equilibrium).

The system, however, may become a victim of its own success. With the capital–labor ratio at 0.2 as in this example, a population of more than double that with low capital levels can be supported (Figure 4(C)). When the population is 24,000, the equilibrium wild resource biomass and soil fertility are both roughly 60% of maximum. However, the unstable equilibrium and boundary between the long-run equilibria has moved up and to the left. Now a moderate or small perturbation can push the system into the undesirable basin (horizontal arrow in Figure 4(C)). Society attempts to recover by intensifying irrigation but, as shown in Figure 4(C), soil fertility is drawn too low during the recovery process, initiating the destruction of both resources. As population grows, the closer the boundary gets to the positive steady state and the more vulnerable the system becomes to local drought. Further, society may misinterpret the effects of its actions during recovery. The wild resource recovers as society intensifies irrigation, so the situation looks positive. However, to allow full recovery of the wild resource, soil fertility must be reduced too far, eventually causing the degradation of the both resources when declining soil fertility forces society to shift back to wild resources (point at which the wild resource stock begins to decline in Figure 4(C)). The sequence of model behaviors shown in Figure 4 may be consistent with the progression of the Hohokam Cultural Sequence through the Pioneer (A), Sedentary (B), and Classic (C) periods.

Figures 3 and 4 correspond to K/h ratios of 0.01 and 0.2, respectively. The model behavior is qualitatively the same for $0.01 < K/h < 0.2$ and for $K/h > 0.2$, except for some minor differences worth mentioning. Increasing K/h amplifies the sigmoidal section of the soil fertility isocline and moves it to the right (compare Figures 3(A) and 4(A)). This has two effects. When population is low and $0.01 < K/h < 0.2$, the qualitative model behavior is the same as Figure 4(A) except that the sigmoidal portion of the soil fertility isocline is smaller and further to the left causing society to switch to irrigated agriculture only after a larger drought and switch back to wild resources earlier during recovery. For intermediate population levels (10,000) and $0.01 < K/h < 0.2$, the humped portion of the wild resource isocline intersects the soil fertility isocline (as in Figure 3), but with a key difference: with more infrastructure, society *can* meet its needs with small-scale irrigation, while in the degraded wild resource base equilibrium.

The story remains unchanged when $K/h > 0.2$ and populations are low. For population sizes above 15,000 increasing K/h beyond 0.2 has a simple effect: it rotates both isoclines clockwise about the origin leaving the boundary between the stable equilibria roughly unchanged. Thus, increased investment decreases pressure on the wild resource (the equilibrium moves rightward) increasing the robustness of the system to local drought just as one would expect. The maintenance of higher levels of irrigation infrastructure, however, introduces vulnerability in the social domain and to floods.

4. The dynamic interplay between social and institutional change and shifting vulnerabilities

The analysis presented above provides a caricature of the leapfrog process of shifting vulnerability and social change. A successful combination of technology and institutions (ball courts and regional trading networks) may cause society to move from Figure 3(A) to 3(B) to 3(C). In so doing, society may become more vulnerable to environmental or social disruptions and may respond by shifting technology (e.g. irrigation intensification resulting in a move from Figure 3 to 4). This shift may either be facilitated by or generate incentives for institutional innovation. If society reorganizes around more intensive technology and associated institutional structures, it becomes much more robust to drought. However, as the notion of 'conservation of fragility' suggests, society may have simply traded-off different vulnerabilities. Due to its success in coping with vulnerability, society may then move from the situation in Figure 4(B) to that in 4(C). The system becomes more unforgiving and vulnerable to any shock that reduces either the capital or resource stocks (drought, flood, social unrest, etc.). In this case, vulnerabilities induce social change that generates new vulnerabilities, which induce further social change, all the while leading to fewer and fewer options for society. Can this general process shed light on the social and institutional changes observed in the Hohokam Cultural Sequence?

Consider the Pioneer period in light of Figure 3(A). Small drought events would lead to nothing more than the population having to forage more intensely, while the resource base recovered. Perhaps a 100-year drought event would be large enough to push the system to the left of the unstable equilibrium after which the system would not recover and degrade further. Only a wetter-than-average period could enable the system to recover. As population increased, ever-smaller drought events would lead to such periods and ever-more exceptional wet periods would be required to enable the system to recover (Figures 3(B) and (C)). Such experiences would provide impetus for the development of more irrigation infrastructure and cause a move from 3(C) to 4(A). If population densities were sufficiently low that growing seasons in which irrigation water was scarce were infrequent, the system may have been managed without large-scale, hierarchical organization. At this point, the linkage between resource users and public infrastructure was most likely based on informal institutions. The Hohokam may have been a non-hierarchical, open society as reflected by the open courtyard settlement patterns with communal resources and active links with other communities through the ball-court system. At this stage, resource users and public infrastructure providers are one and the same, so links 2 and 3 are irrelevant. Link 5, representing the influence of institutions on the relationship between users and resources, would have been maintained by the high levels of trust possible in a small society.

With a larger population, irrigation activity would begin to require additional transactions between agents associated with maintenance, coordination, and rapid labor mobilization for major repairs after floods. Task specialization and increasing trade would also generate additional transaction costs. Reducing these transaction costs would be a strong impetus for institutional change (North and Thomas, 1973) and the more formal ball-court social infrastructure of the Colonial and Sedentary periods would be a natural outcome (Figure 2).

With more formal social infrastructure, the roles of resource users and public infrastructure providers may become more distinct with links 2 and 3 becoming more important over time as elites associated with ball courts possibly emerged.

Further population growth would push the system from Figure 4(A) to 4(B) with irrigation now a continuous, larger-scale activity. Vulnerability to floods would increase with increased dependence on well-functioning irrigation infrastructure. Scarcity of wild resources and irrigable land may generate incentives for the development of more clearly defined property rights and more complex institutions for 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 intergenerational transfer of property would naturally emerge. These processes are consistent with changes during the Classic period. Above-ground walled compounds suggest a clearer definition of personal property. More nucleated communities may indicate extended kin groups, where relatedness became more important because of intergenerational property transfer. Replacement of inhumation with cremation might suggest stronger connections to spatially explicit resources. Complexification of institutions may require that energy and resources be pulled from other pursuits. This is consistent with the contraction of the regional system and a reduction in the production of export goods.

Finally, further population growth might lead to a transition from Figure 4(B) to 4(C). Now, a relatively small drought event could push the system into the basin of attraction of the (0,0) long-run equilibrium. Society could respond by further irrigation intensification, but this would be the straw that broke the camels back. Slow degradation of both the wild and irrigated resources base would ensue. There would be no catastrophic collapse, just slow, inevitable decline. Now society has no options, it cannot further reduce its impact on either resource and can only be rescued by a rare, exceptionally wet period. Alternatively, a flood event may cause a transition from Figure 4(C) to 3(C). Either wild resources would be unable to support the population to rebuild infrastructure and transition back to Figure 4(C) or during the transition wild resources would become so degraded that the system is caught in the (0,0) basin of attraction with no way out other than an exceptionally wet period.

This process could be characterized as natural capital (wild resources) being replaced with institutional capital (more complex rules of behavior, more advanced concepts of rights, etc.) to cope with a fluctuating environment. Maintenance of institutional capital, however, requires significant resource input. 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 complex dwellings. The important question is exactly how much surplus production was possible, what level of institutional complexity could be maintained, and what vulnerabilities emerged.

This increasing institutional complexity may not have required the emergence of hierarchical social organization. It is difficult to know whether hierarchical organization emerges as a matter of necessity, whereby some individuals reluctantly accept responsibility to provide public infrastructure, or as a result of opportunists who exploit the existence of surpluses (Olson, 1982). In either case, a separate group of public infrastructure providers adds new opportunities and problems to the system. Links 2 and 3 in Figure 2 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 strong incentives to shirk their duties of monitoring, sanctioning, coordination, and conflict resolution. They may not invest resources in the maintenance of 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.

Again, signatures toward the end of the Classic period may be consistent with such collective action problems. The key features potentially associated with the coordination of the canal system are the platform mounds. There were many more than those shown in Figure 1(B), 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 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', large structures that seem to serve no practical purpose, near the end of the Classic. Are these structures evidence of surpluses being siphoned off by the elites?

The story of Hohokam transformation in the Classic period and subsequent collapse may thus be a story of the co-evolution of resource use technology 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 wild resources that may have initially driven 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.

5. 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. Based on the framework, a simple formal mathematical model was developed an analyzed. Given the nature of archaeological data, this exercise is necessarily very speculative, but it does focus our attention on a set of interlinked processes that, taken together, engender change. Change may occur when SESs become vulnerable. This vulnerability may come as a cost associated with enhanced robustness in other domains. By carefully examining the nature of the linkages shown in Figure 2 for a particular system, the trade-off between robustness in one domain and vulnerabilities in another may become clearer.

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 an institutional perspective enhance our understanding of archaeological cases? Can we see signatures of changing institutional arrangements, beyond general 'complexification'? For example, can we see manifestations of property rights and strategic interactions between agents? What kinds of archaeological evidence would be required to address such questions? Further research in this area should 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 in different domains that they may face. These principles could help guide present-day policy development regarding long-term environmental change.

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