Archaeology's long-term perspective on irrigation infrastructure and vulnerability

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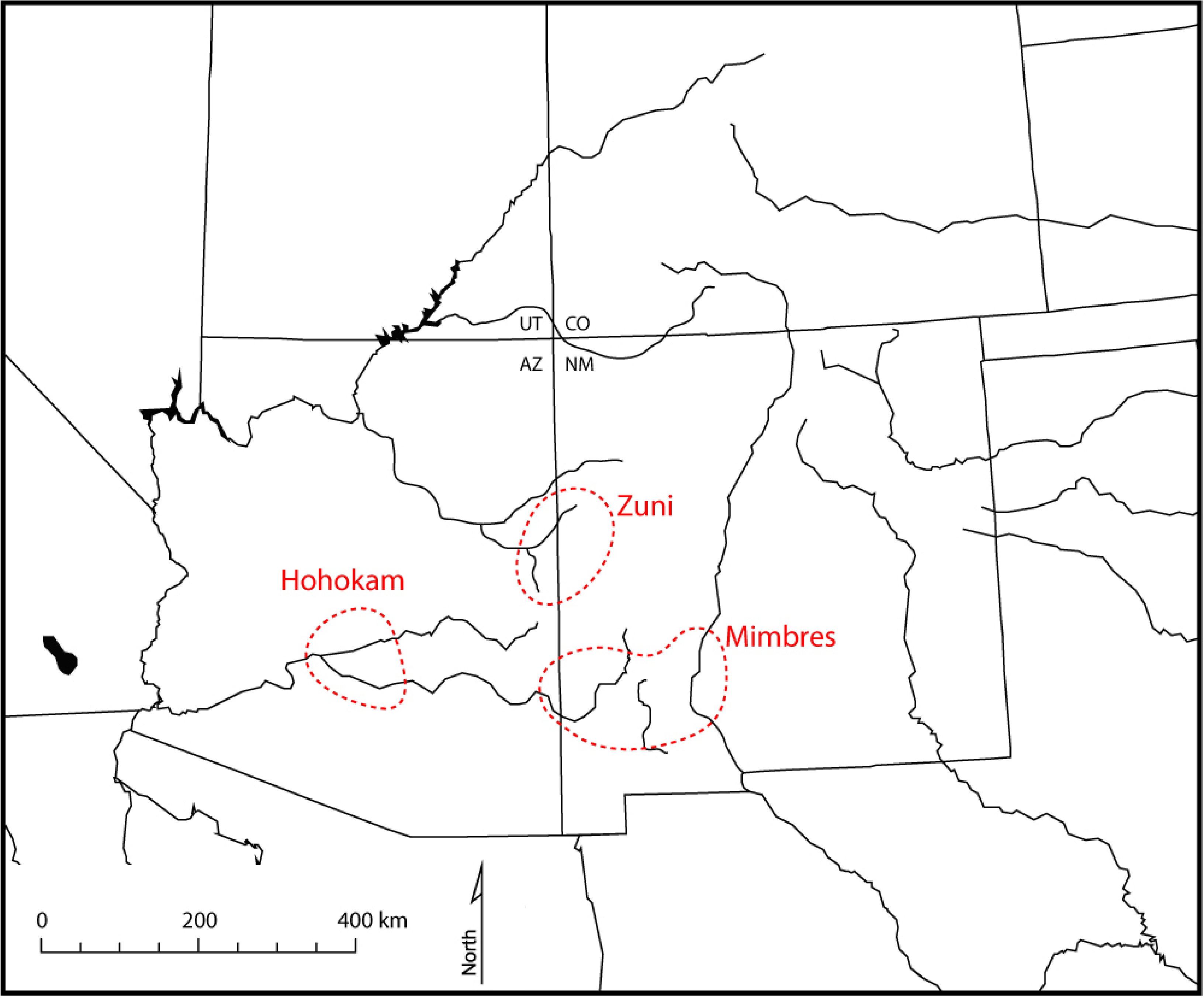
ABSTRACT

What relationships can be understood between resilience and vulnerability in social-ecological systems? In particular, what vulnerabilities are exacerbated or ameliorated by different sets of social practices associated with water management? These questions have primarily been examined through study of contemporary or recent historic cases. Archaeology extends scientific observation beyond all social memory and can thus illuminate interactions occurring over centuries or millennia. In this paper we examine trade-offs of resilience and vulnerability in the changing social, technological, and environmental contexts of three long-term, prehispanic sequences in the US Southwest: the Mimbres area in southwestern New Mexico (AD 650-1450), the Zuni area in northern New Mexico (AD 850-1540), and the Hohokam area in central Arizona (AD 700-1450). In all three of these arid landscapes, people relied on agricultural systems that, in turn, depended on physical and social infrastructure that diverted adequate water to agricultural soils. But across the cases, investments in infrastructure varied as did local environmental conditions. Zuni farming employed a variety of small scale water control strategies including centuries of reliance on small run-off agricultural systems; Mimbres fields were primarily watered by small-scale canals feeding floodplain fields; and the Hohokam area had the largest canal system in prehispanic North America. The cases also vary in their historical trajectories; at Zuni, population and resource use remained comparatively stable over centuries, extending into the historic period, while in the Mimbres and Hohokam areas there were major demographic and environmental transformations. Comparisons across these cases, thus, allow us to understand factors that promote vulnerability and influence resilience in specific contexts.

In a recently published special issue of the *Proceedings of the National Academy of Sciences,* Ostrom and her colleagues (2007) argue that single, overarching solutions to sustainability issues are doomed to failure because they are overly optimistic about the similarity in the characteristics of resource problems, preferences, information, and the actors across the many different contexts in which they might be applied. With respect to water institutions, Ruth Meinzen-Dick (2007:15200) argues "research that identifies the critical factors affecting irrigation institutions can lead to sustainable approaches that are adapted to specific contextual attributes." The key phrase here is "adapted to specific contextual attributes", highlighting the fact that panaceas or generalizations about how sustainability can be achieved fall short because of the variability in local social and environmental conditions. Although Meinzen-Dick and others in the Ostrom et al. volume are typically referring to small-scale social-ecological systems embedded in modern state-level systems, their insights apply broadly to water control systems used by agriculturalists. As they argue, *context matters*. In this paper we examine the changing role of social context in the realization of the long-term performance of three water management systems.

Important determinants of the performance of social-ecological systems include the biophysical context (e.g. topography, biogeochemistry, ecology) and infrastructure (e.g. physical capital, institutions, social capital). Infrastructure in arid environments can be structured to cope with spatial and temporal variability in water availability and to increase productivity (Schlager et al. 1994; Janssen et al. 2007). Irrigation and storage infrastructure, for example, can promote resilience to specific kinds of environmental variation. But they also anchor people to particular locations, foreclosing options such as mobility, and may generate new vulnerabilities to other social and environmental conditions (Anderies 2006; Janssen et al. 2007). Previous research by ourselves and others using both modeling and archaeological data indicate that while irrigation systems may facilitate economies robust to short term variation in precipitation, they may also contribute to vulnerabilities that sometimes lead to costly transformations (Abbott 2003; Anderies 2006; Graybill et al. 2006; Hegmon et al. 2008; Howard 1993, 2006). A trade-off between vulnerability to short- and long-term fluctuations is known to be fundamental property of a large class of simple dynamical systems (Bode 1945). This fundamental property implies that it is challenging to be robust to fluctuations that occur with an annual frequency and those that occur once every 50 years.

In this paper, we explore the trade-offs in robustness/vulnerability in three prehispanic cultural sequences (Figure 1) dating from AD 650 to 1540 in the US Southwest, all of which are agricultural societies dependent on water management: the Mimbres area in southwestern New Mexico (AD 650-1300), the Zuni area in northern New Mexico (AD 850-1540), and the Hohokam area in central Arizona (AD 700-1450). By comparing these cases we can evaluate, over the long term, how the different physical and social infrastructural contexts affected the persistence of farming societies. Our cases share key features: they are located in similarly arid landscapes in which dryland agriculture is tenuous to impossible; all have similar cropping systems and crop mixes that rely on maize; and these agricultural systems depended on physical and social infrastructure that concentrated water on agricultural soils. But on close inspection, they are quite different in ways that are important to understanding their persistence or collapse. Across the cases, investments in infrastructure varied as did local environmental conditions. Zuni farming employed a variety of small scale water control strategies including centuries of reliance on small run-off agricultural systems; Mimbres fields were primarily watered by small-scale canals feeding floodplain fields; and the Hohokam area had the largest canal systems in prehispanic North America. The cases also vary in their historical trajectories; at Zuni, population and resource use remained comparatively stable over centuries, extending into the historic period, while the Mimbres and Hohokam areas experienced major demographic and environmental transformations. For these three cases, we explore how changing social and environmental contexts influenced the trade-offs between different classes of vulnerabilities, and


UT
CO
AZ
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Zuni
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Mimbres
0
200
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in some cases, resulted in the realization of potential vulnerabilities as evidenced in large scale social-ecological transformations.

Sustainability, Resilience, and Vulnerability

Our comparison benefits from resilience theory, which suggests that since change is inevitable, a management policy that integrates adaptation to change is preferable to one that manages *against* change (Folke et al 2002). It has been suggested by some who use resilience concepts to understand change in contemporary and recent historical socioecological systems, that efforts to improve resilience of a system always involve trade-offs. Anderies and others (Anderies 2006; Anderies et al. 2006; Anderies et al. 2007; Janssen et al. 2007; Scheffer et al. 2001) have suggested that resilience, at a particular focal scale, is not an absolute; rather to understand resilience, we must consider trade-offs between robustness and vulnerability with respect to different classes of uncertainties. In evaluating modern fisheries as well as prehispanic water control systems for agriculture, Anderies and his colleagues have found that "policies robust to uncertainty in one group of parameters are necessarily vulnerable to uncertainty in another group" (Anderies et al. 2007:15194). The best we can expect to do is to minimize susceptibility to selected vulnerabilities and manage for resilience to uncertainty.

In addition, resilience trade-offs may be occur among social groups and across temporal and spatial scales. For example, especially in arid environments, water use by one group may create externalities for others. In agricultural systems depending on large canals, water-use that creates benefits for one user group or individual may result in shortfalls for others. Thus, shared water resources require management—or at least coordination. But additional trade-offs exist in the *scales* of management or control over the water resources. Local users controlling water infrastructure generally have better contextual knowledge of local conditions but may not sufficiently understand the impacts of their decisions at the regional scale, depending on the scope and effectiveness of communication and group deliberation (Meinzen-Dick 2007). These facts and observations lead us to a folk theorem of sorts: vulnerability cannot be eliminated from a system, it can only be moved across spatial and temporal scales or across system components. The use of physical and social infrastructure by groups to reduce vulnerability to annual environmental variation introduces new vulnerabilities in the social domain and to events that occur at much larger spatial (basin versus local) or temporal scales (annual versus century). To evaluate the implications of this folk theorem, we need case studies that span sufficient spatial and temporal scales to observe if and how trade-offs play out. Here we investigate three such cases that share similar types of infrastructure (water management in arid environments) but that played out in different ways.

It is almost universally the case that hunting and gathering strategies are quite robust to diverse environmental conditions but can support only very low population densities. In many arid settings, including much of the US Southwest, supporting even modest population densities requires a substantial investment in agriculture. And, in nearly all of the southwest US, successful agriculture requires some form of water control to cope with low absolute levels of precipitation and available groundwater, as well as high levels of short-term spatial and temporal variation in precipitation (Spielmann et al 2009). In this paper, we focus on trade-offs of robustness and vulnerability created by water control systems that underwrite agriculture, attending to the scales of control and differential advantages for social groups. Different forms of water management can enhance robustness to different sorts of climatic and hydrologic conditions. New areas can be made productive and productive areas made more reliably productive with controlled distribution of water. As a consequence, greater numbers of people and concentrations of people can be supported. The extent to which productivity is enhanced, among other things, depends on the form, size, and scale of the physical infrastructure.

We are interested in the potential vulnerabilities associated with this enhanced productivity; we emphasize “potential” because the way in which vulnerabilities “play out” over the long term depends, in part, on the dynamic socioecological context and in part on environmental variability and environmental change. We identify three, among many, potential vulnerabilities in different domains:

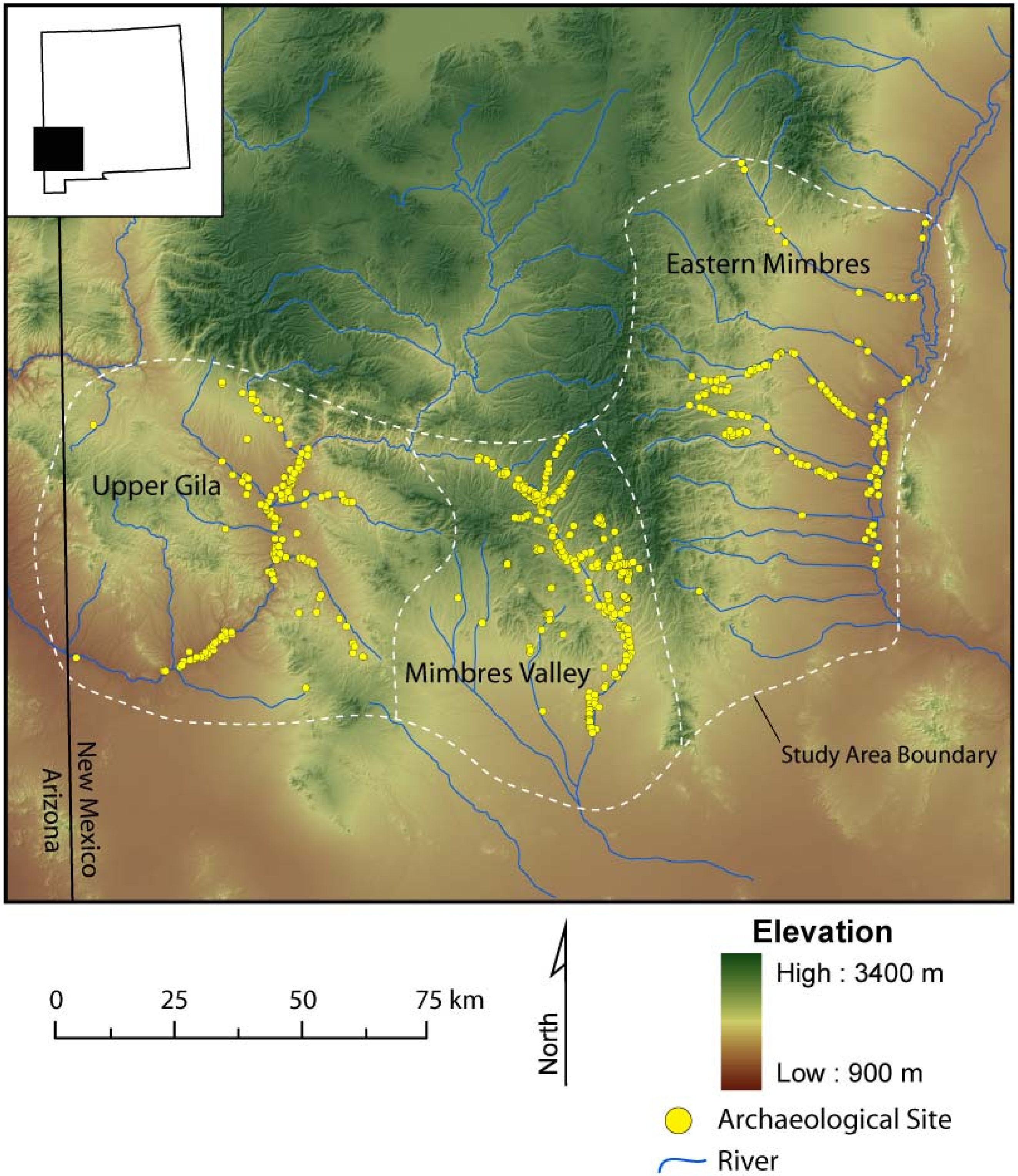
1. The physical infrastructure of water control systems may be vulnerable to rare climatic events such as major floods or droughts. This is the trade-off between robustness to high frequency shocks and vulnerability to low frequency shocks, which we refer to as shock frequency. Once the food production system depends on water delivery, the level of production can be disrupted by climatic events. However the effects of major events can be softened by implementing alternative food production strategies not impacted by the same climatic circumstances. Thus, maintaining diverse water control systems or varied farming strategies in different settings, while potentially costly on average, might ameliorate vulnerability to rare climate events.
2. The commitment to place entailed by physical investments in infrastructure can increase residential stability or duration of occupation at settlements. In arid settings, local resources such as soils, animals, and plants can be depleted, sometimes permanently, by long-term occupations. In resilience terms, the connection to place can reduce adaptive capacity or response capacity. And, for millennia, residential movements were key to the long-term resilience of socioecological systems for much of the prehistoric US Southwest.
3. Despite increased productive capacity, increasing population and increasing spatial concentration of population into larger villages and towns (which we call aggregation), can exceed the capacity of local resources, including those enhanced by the water control infrastructure. The slow variable of population increase is traded off against the control over short-term food productivity. However, movement and exchange of goods can ameliorate this source of vulnerability by redistributing goods and people.

The extent to which these vulnerabilities may contribute to transformations depends on the socioecological context and changes in that context over time. We describe the agricultural systems and contexts of three prehispanic cases that we can trace over several centuries. For each case, we look at the trade-offs of robustness and vulnerability attributable to each water control system and the extent to which specific vulnerabilities may have contributed to observed transformations in their specific contexts. By comparing the three cases, we can see the long-term effects of tradeoffs in high and low frequency shocks, response capacity in different domains, and between fast and slow variables.

The Mimbres: ditch irrigation and social reorganization

“Mimbres” refers to an archaeologically defined region is in southwest New Mexico of approximately 19,000 square km (Figure 2), as well as to the spectacularly decorated pottery made there (Brody 1977; Anyon et al. 1981; LeBlanc 1983; Hegmon 2002). During the period from AD 650–1300, gradual change was punctuated in the mid 12th century by a substantial transformation in which the regional population declined and social institutions reorganized. Less dramatic than the Hohokam case of total population collapse (discussed below), people in the Mimbres region reorganized and many remained in the area. We explore how the potential vulnerabilities of water control infrastructure may have played a role in the scale and magnitude of this reorganization (as compared to our other two cases.).

The subsistence economy of the entire sequence can be characterized as a long period of small-scale farming supplemented by hunting and gathering. Up until AD 1000, settlement remained dispersed, focused regionally around ceremonial structures that were intentionally destroyed in the early 900s (Creel and Anyon 2003). The subsequent Classic period (AD 1000–


Eastern Mimbres
Upper Gila
Mimbres Valley
Study Area Boundary
New Mexico
Arizona
0
25
50
75 km
North
Elevation
High : 3400 m
Low : 900 m
Archaeological Site
River

1130) was characterized by increased social and technological capitalization, including aggregation of the population into large villages and an inward-focused regional social network. A reorganization of public ceremony, toward focus on smaller ceremonial spaces controlled by specific households within villages, accompanied this shift toward larger villages. The end of the Classic, which coincided with a severe dry period ca. AD 1130, included depopulation of nearly all villages and the virtual disappearance of the famous pottery style. The effects of this sweeping mid-1100s transformation were more dramatic in the densely populated Mimbres Valley, leading to greater depopulation and environmental depletion (Hegmon et al. 2008; Minnis 1985; Sandor 1992) than in the drier and environmentally patchier eastern Mimbres area. Villages were depopulated in part by emigration and in part by dispersion to small settlements (Hegmon et al. 2000; Nelson 1999). Within a half century (ca. AD 1200), the local population and immigrants from both the north and the south had again aggregated into new villages in the region, some located adjacent to the Classic villages.

Mimbres Agricultural System

The agricultural system of these prehistoric farmer-hunter-gatherers was oriented primarily toward the floodplain of the major rivers and tributary drainages, and was supplemented with run-off farming on hill slopes and alluvial fans. The irrigation system consisted of a series of short canals or ditches, feeding local floodplain fields. We have no evidence that these were linked in such a way that residents of one village controlled the water flow to the fields of other villages, except that upstream drawdown may have influenced downstream use, especially under conditions of low precipitation. This small-scale irrigation system increased productivity of floodplain fields as did the stone terracing systems on hill slope and alluvial fan fields, insuring more directed and abundant water and nutrient flow to field locales. Increased productivity and potential for food storage increased robustness of the food supply to localized fluctuations in precipitation. The diversity of field locales and water-directing technologies also improved robustness of the food supply to the variable spatial distribution of precipitation in the region.

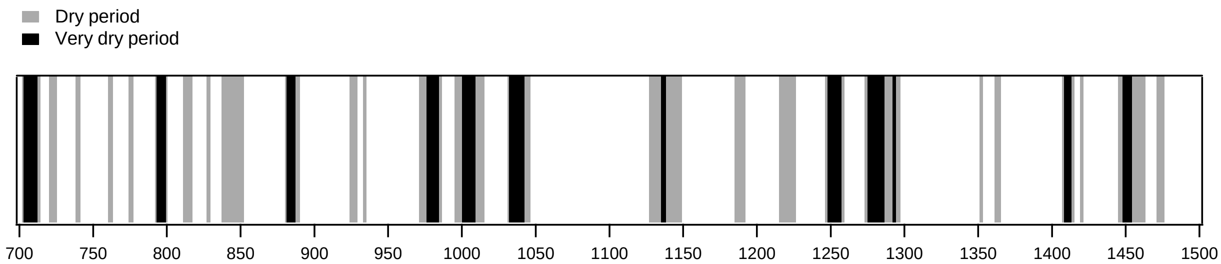
Realization of Potential Vulnerabilities

How did these advantages of agricultural productivity and predictability of food supply created by the agricultural infrastructure trade off over the centuries against the potential vulnerabilities associated with such a system? Might they have contributed to the 12th century transformation? Recall we have identified three of the potential vulnerabilities to be a) the effects of rare climate conditions, b) the effects of place focus on degradation and depletion of resources, and c) the effects of increased capacity to support local population on eventual resource stress especially in dry years. Their actual impact is influenced by the changing social context of the Mimbres region.

a) ***Potential impacts of rare climate conditions (shock frequency trade-off)***: In this region of the US Southwest, declines in precipitation and changes in the temporal and spatial variability of precipitation influence productivity. While water control can ameliorate most high frequency variation, rare climatic events may have a greater impact on the food supply when the subsistence economy of farming is focused on the field areas supplied by water control systems, primarily the floodplains of rivers and creeks in the Mimbres region. Severe dry periods reduce the sprouting and growth of cultigens, floods can destroy fields and water control infrastructure, and lowered water table can make irrigation systems dysfunctional.

Our climate data are limited to severe dry periods. Ingram has analyzed dendroclimatological records to identify the extreme low precipitation periods through over a millennium of occupation in the region (Figure 3).[1] Many periods of severely low precipitation were experienced during the temporal interval discussed here, and most were not associated with social transformations that are evident in the archaeological record. However, the extended period of extremely low

Figure 3 Periods of extremely low precipitation in Mimbres Region



Precipitation reconstruction (Central Rio Grande) developed by Grissino-Mayer, Baisan, and Swetnam (1997). Droughts identified by Ingram (2008).

precipitation around AD 1130 does coincide with the Classic Mimbres village depopulation. Why might it have been a factor at that time and not before or after? The late 11th and early 12th century was a time when increased population, place-focused settlement, and limited regional connectivity converged to make this potential vulnerability a reality. These social factors are addressed below.

b) ***Residential stability and the potential for depletion of resources (local focus and reduced response capacity)***: In the arid to semi-arid US Southwest during the prehistoric period, depletion of plant and animal resources (Janssen et al. 2003; Kohler 1992; Kohler and Matthews 1988; Nelson and Schollmeyer 2003), and of soils (Sandor 1992) occurred often and arguably contributed to major transformations (Minnis 1985; Janssen et al. 2003) as it has elsewhere in the world (e.g., Kirch 2005, 2007; van der Leeuw 1998, 2005). Our analyses and those of Sandor indicate that with the dense and continuous occupation at some locales, game and soil resources could have been depleted within a few years (Nelson and Schollmeyer 2003; Sandor 1992; Schollmeyer 2009).

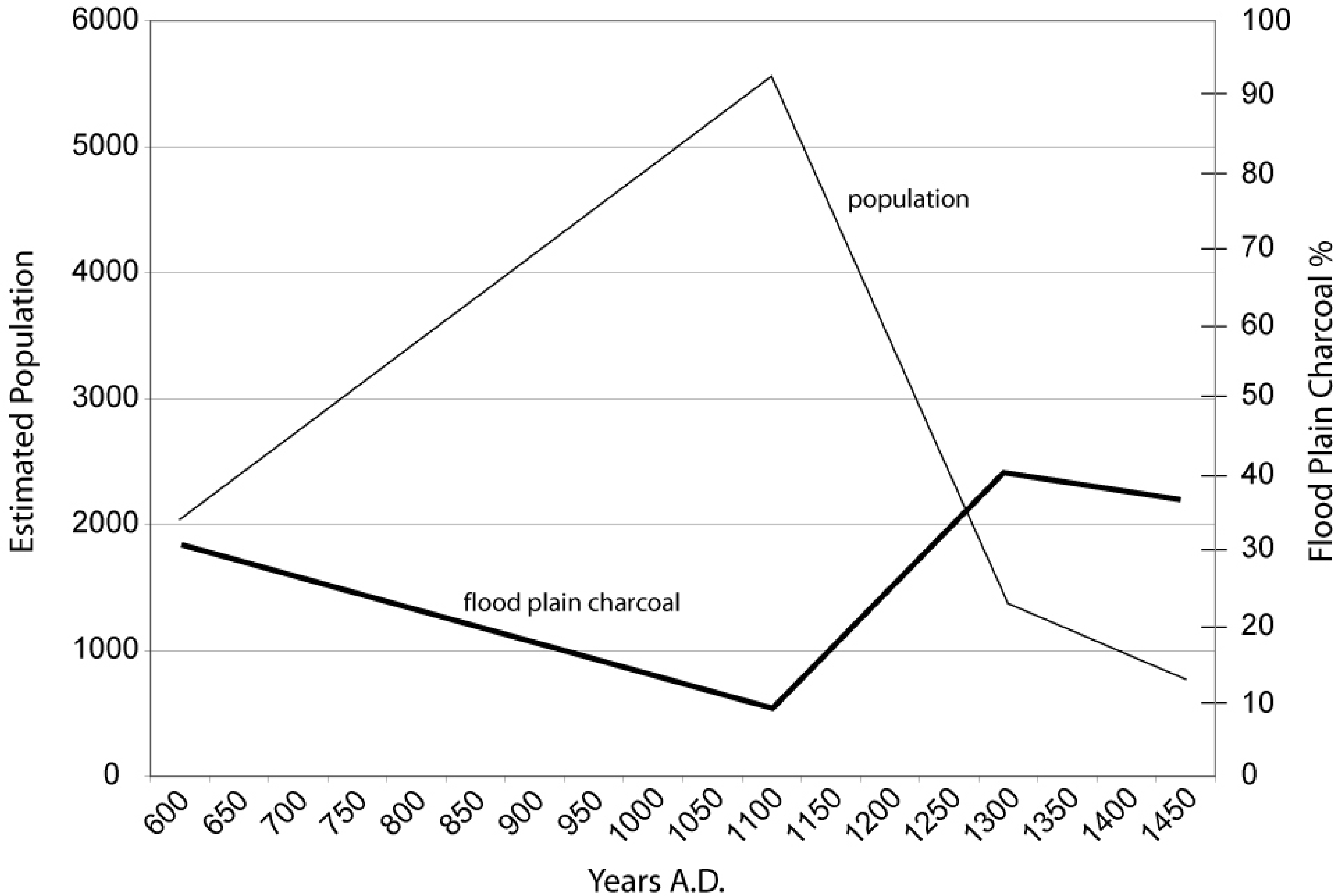
Residential stability, the long-term and continuous occupation of places (Horne 1993; Nelson 1999; Rocek 1996; Stone 1996), contributes to resource depletion in the areas surrounding settlements. In the US Southwest, settlement shifting or what archaeologists call "residential mobility" was common (e.g., Nelson 1999; Schlanger and Wilshusen 1993; Varien 1999). But investments in physical infrastructure encourage stability and place-focused settlement. In the Mimbres region, prior to the 11th century, people shifted settlements frequently (Swanson 2009; Swanson and Diehl 2003). By the beginning of the 1100s, a greater place-focus emerged with long-term settlements relatively evenly spaced along the major rivers and tributaries (Blake et al. 1986; Nelson 1999).

Minnis has documented a depletion of local riparian vegetation during the 11th to early 12th centuries in the Mimbres Valley, concurrent with the shift toward residential stability, as land was cleared for fields (Figure 4); Schollmeyer (2009) has argued for a depletion of game resources, as well. Thus, as residential stability replaced mobility during the 11th and early 12th centuries, the potential for depletion of resources central in the diet of village dwellers was realized. Not only were the plant and animal resources depleted, but soils in secondary fields on upland slopes, made productive with water-directing stone terraces, were also depleted through compaction from repeated use (Sandor 1992).

c) ***Potential for population growth and demand on food supply (slow-fast variable trade-off)***: Population size and the concentration of population on the landscape directly influence the potential for food stress, especially in an arid and semi-arid landscape. In the Mimbres region, population remained dispersed until the 11th century at which time large, pueblo-style villages were formed. Table 1 shows the pattern of population aggregation, showing a 75% increase from the Late Pithouse to the Classic period from 44 sites to 77 sites with 50 or more dwellings, which we consider to be aggregated villages. This focused population created increased demands on local resources. At the same time, the overall regional population increased. Figure 4 shows the pattern of change in population size from the 600s to the 1400s, with the peak in the Classic Mimbres period.[2]

Minnis has argued that the social, demographic, and environmental conditions of the Classic Mimbres period may have created food stress, at least in the Mimbres Valley. Although available analysis of human remains from Classic Mimbres sites indicates no substantial evidence of poor diet (Gruber 2007; Holliday 1996; Lippmeier 1991), the perception of shortfall or the short-term experience of shortfall can influence decisions to move or reorganize.

Vulnerabilities and Transformation


Estimated Population
Flood Plain Charcoal %
population
flood plain charcoal
Years A.D.
0
1000
2000
3000
4000
5000
6000
0
10
20
30
40
50
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600
650
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1000
1050
1100
1150
1200
1250
1300
1350
1400
1450

Table 1: Population aggregation pattern in the Mimbres Region.

Time Period	Date Range	Number of Sites by Room Count			
		Less than 50	50-100	200-300	Total
Late Pithouse	AD 700-1000	94	44	0	138
Classic	AD 1000-1130	230	66	11	307
Reorganization	AD 1130-1200	16	0	0	16
Early Postclassic	AD 1200-1300	40	20	2	62
Late Postclassic	AD 1300-1450+	21	14	3	38

Thus, a number of factors coalesced to realize the potential vulnerabilities in the 12th century Classic Mimbres period. Although extreme climate conditions and resource depletion were regular conditions throughout the entire sequence, they became substantial vulnerabilities because of the increased population and greater residential stability of the Classic period. The agricultural systems that had enabled greater population eventually utilized all the available floodplain field areas and extended broadly into upland areas to alluvial fans and hill slopes. That population collapsed in the mid-12th century (the end of the Classic period) under extended conditions of low precipitation. Nonetheless, the partial depopulation of the Mimbres region cannot be attributed entirely to the any one factor.

While the system eventually became vulnerable to low precipitation years, people might have counteracted the low productivity of those years through several social and economic strategies: increasing use of local wild resources, engaging in extensive exchange, or shifting settlement location. Two social conditions increased vulnerability under the conditions that had developed. The first was an inward focus in social relations; the people of the Mimbres region appear to have engaged in little exchange of goods or people with those of the adjacent and thriving Hohokam and Chaco regional systems (Hegmon and Nelson 2007). Their social boundedness precluded the option of exchange to ameliorate risks of shortfall (Minnis 1985) and may have made movement away from their villages difficult because of a lack of broad-scale social networks. Cross-scale social vulnerabilities combined to contribute to demographic decline and institutional collapse.

The second condition increasing their vulnerability was the residential stability driven by investments in physical infrastructure, land tenure, and social history. With the depletion of wild resources and destruction of land cover brought on by residential stability, the reservoir of productive local plants, animals, and soils was reduced. A series of low precipitation years that under other conditions (lower population, more extensive exchange, and higher residential mobility) of earlier and later periods could have been addressed, contributed to the depopulation of nearly all villages in the region.

Interestingly, it is residential mobility that did allow some people to remain in the region. The end of the Classic period was not a complete collapse or depopulation of the region, as has been documented elsewhere in the US Southwest. Rather, for some it was a regional reorganization marked by a shift from large villages to dispersed hamlets and extensive social networks (M. Nelson 1999; M. Nelson et al. 2006), responses that that might have ameliorated some of the vulnerabilities of the Classic system. Change at the village level allowed people to remain in their homeland, maintaining stability at a regional level (Hegmon et al. 1998; M. Nelson 1999; Nelson and Hegmon 2001; M. Nelson et al. 2006). This well-studied Reorganization phase following AD 1130 (Hegmon et al. 1998; M. Nelson 1999), illustrates the processes of release and reorganization, known as the alpha and omega phases in resilience theory (M. Nelson et al. 2006).

Following the Reorganization phase in the mid 13th century, people shifted back into aggregated villages; they had abandoned a recognizable Mimbres identity and developed extensive ties to outside areas, resulting in some of the most diverse pottery assemblages known in the US Southwest. With the renewed residential mobility and a decline in population, many of the resources depleted during the Classic Mimbres period recovered (Minnis 1985; Schollmeyer 2005). When people eventually re-aggregated, population levels were dramatically lower and impacts on local ecosystems were lessened.

The analysis of long-term change in the Mimbres case allows us to track a specific robustness-vulnerability trade-off that may have induced a transformation to a different strategy that moved the system from a local to regional focus. The robustness-vulnerability characteristics of the Classic system were simply untenable for the ecology of Mimbres region. The realization of a vulnerability generated by a strategy aimed at increasing robustness to a specific type of environmental variation engendered a transformation to a new phase of development.

The Zuni: Shifting Agricultural Strategies

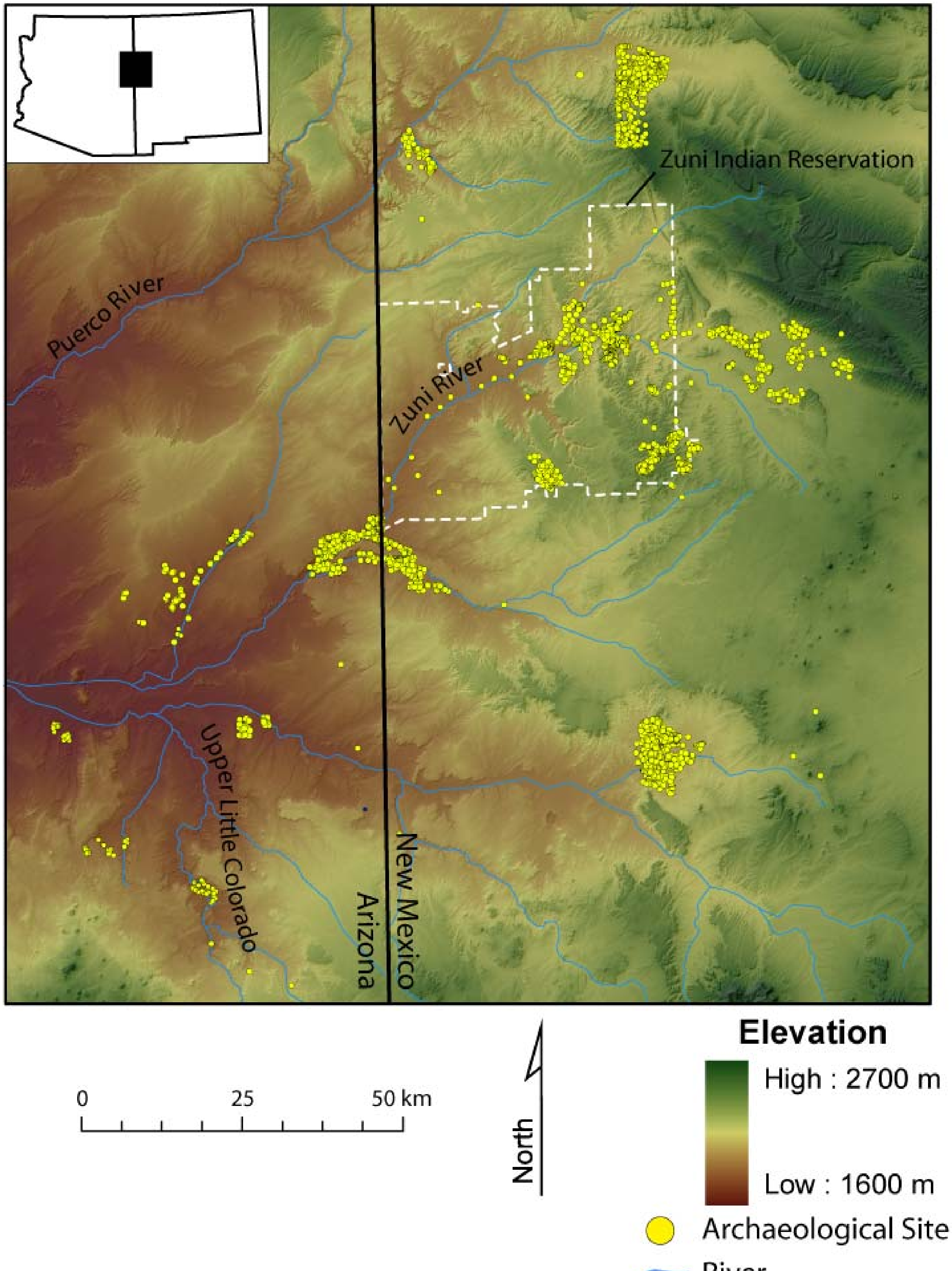
The Zuni area (Figure 5), which spans the Arizona-New Mexico border along the southern margin of the Colorado Plateau is one of only three areas in the Southwest continuously and densely occupied from the early centuries AD, through the Spanish Conquest, and up to the present (Ferguson and Hart 1985) Thus, it is in some sense the most robust of our three cases. Our research covers the period AD 850 to 1540. Excellent, long-term environmental and settlement data and a precise chronological framework enable detailed analyses of long-term changes at generational resolution (e.g., Dean 2007; Van West and Grissino-Meyer 2004). By AD 900, large pit house villages with communal architecture joined small, dispersed settlements dotting the landscape but disappeared shortly thereafter. During the 11th-century, Zuni settlement systems reached their greatest spatial extent, exploiting a wide range of local environments across a range of elevations. By the mid 1200s, aggregated upland settlements with as many as 500 rooms appeared. Through this temporal interval, the focus of population generally moved eastward and toward higher elevations and there was a steady contraction of settled areas (Peeples and Schachner 2007).

By AD 1300 virtually the entire population appears to have aggregated into villages consisting of single structures with from 150 to perhaps 2000 rooms (Kintigh 1985, 1996; LeBlanc 2001; Kintigh et al. 2004) located almost exclusively in upland (ca 2100m elevation) areas. Nonetheless, settlements predating AD 1400 typically lasted from a few years to no more than a generation and never more than a century. Between AD 1350 and 1400, the entire population moved downstream (ca 250m lower in elevation) to a few large, long-lasting protohistoric towns along the Zuni River. One, Zuni Pueblo, is still occupied (Kintigh 1985, 2000). While precise demographic estimates are difficult and data are notably sparse for the period from AD 1325-1400, it appears that the population of the Zuni area continued to grow from the earliest times considered here until the mid or late AD 1200s. From that time on, the population probably declined somewhat but the population density in the occupied area remained high.

Zuni Agricultural System

Direct evidence of Zuni agricultural features is limited, but we can infer quite a bit from the site locations and other available evidence. From AD 850-1250 the population was widely distributed but the overall trend was movement from lower to higher elevations. The paleoenvironmental data indicate that the period from AD 925-1250 was generally favorable for agriculture in a variety of settings (Dean 2007). Many of the earlier sites, both large and small, were on duned ridges overlooking areas with substantial floodplains of what are now intermittent streams, suggesting dispersed floodplain and sand-dune agricultural fields watered by ground water and floodwater, perhaps augmented with runoff (*ak chin*) farming. With a lower water table, the period from 1250 to 1450 was favorable for runoff farming, but disadvantageous for floodplain farming. We have some direct evidence of terracing and other forms of runoff farming dating to the beginning of this interval. The AD 1250-1350 preference for runoff farming is also reflected in the settlement patterns, with habitation concentrated in upland areas where appropriate topographic settings for runoff farming were concentrated. After 1300 people increased their use of upland settings adjacent to larger springs or other permanent water sources where small-scale irrigation could be practiced in combination with runoff agriculture. The shift to downstream locations of the protohistoric sites, between A.D. 1350 and 1400, was almost entirely to settings on broad floodplains adjacent to the Zuni River or its major tributaries, where runoff farming was not possible. These settlements would have required a heavy reliance on irrigation agriculture.

Realization of Potential Vulnerabilities


Zuni Indian Reservation
Puerco River
Zuni River
Upper Little Colorado
New Mexico
Arizona
0
25
50 km
North
Elevation
High : 2700 m
Low : 1600 m
Archaeological Site
River

In the Zuni area, how did these advantages of a productive and predictable food supply, enabled by agriculture, trade off with potential vulnerabilities? We again consider the three potential vulnerabilities discussed above: a) the effects of rare climate conditions, b) the effects of place focus on degradation and depletion of resources, and c) the effects of increased capacity to support local population on eventual resource stress especially in dry years.

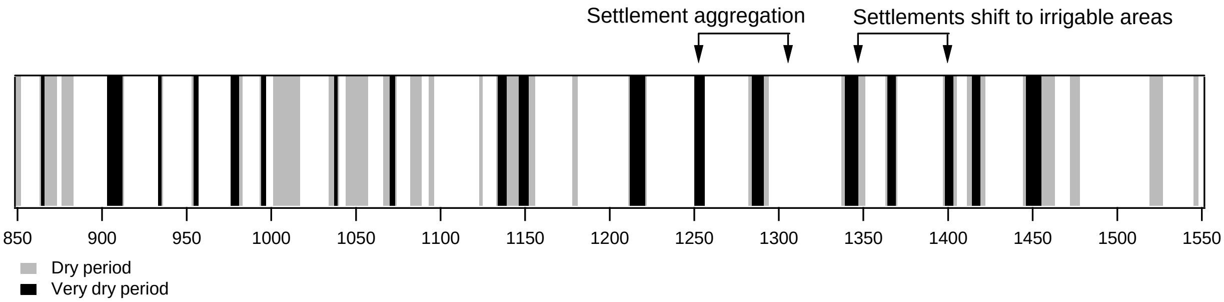
a) Potential impacts of rare climate conditions (shock frequency trade-off): The apparent robustness of the system—including through periods of extremely low precipitation from AD 1120 to 1160 and 1275 to1300—is indicative not of a stable adaptation but of a flexible set of strategies that were employed in response to both high and low frequency environmental variability (such as annual spatial and temporal variability in precipitation and hydrological cycles several centuries long). Thus, as the water table dropped, floodplain settings were abandoned in favor of ones in which runoff agriculture was possible; in longer periods of depressed or increased moisture or temperature, settlements were moved as elevation-dependent zones with sufficiently long growing season for maize shifted, expanded or contracted (Figure 6).

The AD 1350-1400 shift to locations where irrigation was possible represents a major shift in subsistence strategy. Prior to this time, adaptation to short-term variability in precipitation and length of the growing season was probably accomplished, at a village—and likely a household level—by simultaneous exploitation of topographically diverse settings. Responses to long term shifts in hydrology and shortening of growing seasons was accomplished by the movement of settlements. The irrigable locations exploited after AD 1400 were in areas and at elevations that had consistently generous growing seasons. The springs exploited were large and have continued to be highly productive through historic droughts (e.g., AD 1945-1964) and probably during the prehispanic lows from 1350 on, as well (Figure 6). The towns depending on riverine irrigation exploited the Zuni River, whose large watershed would have buffered spatial variability in precipitation.

b) *Residential stability and the potential for depletion of resources (local focus and reduced response capacity)*: A relatively high level settlement mobility characterized the Zuni sequence up until the mid to late AD 1300s. Villages were typically occupied for less than a generation and in some cases for only a few years. Indeed, soil depletion may help explain the high level of residential mobility in a context of low labor inputs in water control infrastructure that characterized the period from AD 850 to about 1300. The historic water control features described by Cushing in the late 1800s (Cushing 1979 [1884]) consist largely of perishable materials located in settings subject to alluviation. Their construction did not involve large time investments or work by large labor parties. If the prehistoric fields were similarly constructed and located, as seems likely, they would generally be archaeologically invisible. We do not have sufficient evidence to fully evaluate this argument. However, preliminary investigations of some unusual Zuni area field locations with exposed small artificial terraces indicated compaction and depletion of soil nutrients (as indicated, among other things by an absence of modern vegetation 700 years after the end of their use). On the other hand, in experimental runoff fields at Zuni, Muenchrath (Muenchrath et al. 2000) showed that, in some settings, substantial nutrients and sediments would have been delivered to these runoff fields to replenish them.

After AD 1350-1400, there was much greater commitment to place, as villages were generally occupied for centuries rather than a few decades. We do not have direct evidence of the prehistoric irrigation features, in part because many of the best locations have been farmed from then until the present day. However, the spacing of the towns along the river and the topography suggest that while canals may have served many households they would have served at most a single town. Whether or not the labor investment in the construction of irrigation facilities exceeded that of the runoff fields considered in the aggregate (as seems likely), it is clear that the maintenance costs would have been much greater and their operation would have required much more coordination at a larger social and spatial scale than the use of runoff fields. This suggests

Figure 6 Periods of extremely low precipitation in Zuni Region



Precipitation reconstruction (Cibola) developed by the Laboratory of Tree-ring Research, University of Arizona (Dean and Robinson 1978).
Droughts identified by Ingram (2008).

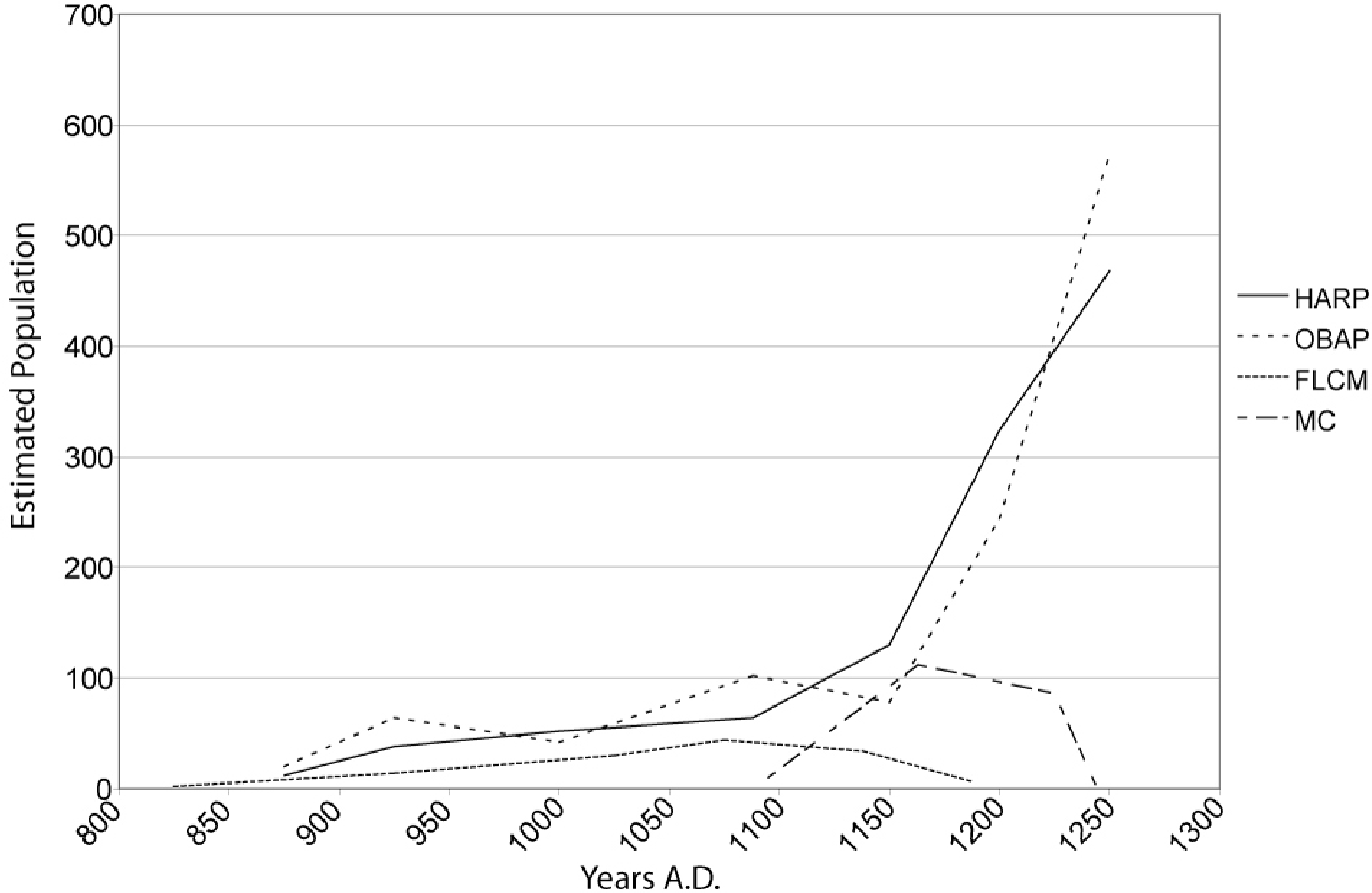
an increased commitment to place that is consistent with the very much longer occupations of these towns. We are not aware of scientific studies of the irrigated fields, but modern field locations adjacent to several late prehistoric and protohistoric towns that used the same water sources were intensively farmed in the 19th century and some are still productively farmed today, suggesting that soil depletion in at least some locations was not a major problem, even in the long term.

Throughout this sequence, important resources were obtained from hunting and gathering, which doubtless mitigated agricultural shortages, though with the population densities experienced in later years, it is likely that both plant and large animal (deer and antelope) resources would have become depleted near the villages. Our faunal data indicate that a protein deficit due to the depletion of large mammals associated with increasingly aggregated settlements may have been offset by raising domesticated turkeys in increasing numbers (Spielmann and Angstadt-Leto 1996).

c) ***Potential for population growth and demand on food supply (slow-fast variable trade-off)***: In the absence of much systematic survey it is difficult to assemble reliable, regional-scale population data because of the temporally variable and spatially patchy distribution of population on the landscape. However, demographic data derived from large, individual systematic archaeological surveys (e.g. Kintigh et al. 2004) show small initial populations with considerable (if variable) population growth up until a time at which the population dramatically declined (Figure 7). Both the numbers and the average sizes (measured in numbers of rooms) of the settlements increased from about AD 850 until 1275. This pattern is repeated throughout the areas occupied by the short-lived settlements that precede AD 1350 (Peeples and Schachner 2007). While localized demographic collapses happened at different times in different places, the data suggest a growing regional population up into the 1200s. Because villages dating to this period were relatively dispersed, small, short-lived, and associated with abundant potential field locations, the vulnerabilities to population growth were probably relatively low.

By the late AD 1200s and continuing into the historic period, the regional population was all concentrated in a small number of large towns with from 150 to about 2000 dwellings. Archaeologists have probably identified all of these very large villages and have general estimates of their sizes. Prior to the move to downstream locations in the late 1300s, population concentration would have simultaneously resulted in increased vulnerability to environmental variability and increased the vulnerability to social discord. There would have been limited locations for productive fields within reasonable walking distances of these large towns. A sustained population would have put significant pressure on the resources themselves and fostered competition among households for favorable field locations. An increasing population would have only exacerbated these vulnerabilities.

Although we can estimate the maximal size of the long-lived protohistoric towns (AD 1400-1540), the data do not exist to reconstruct the demographic trends within this period. The archaeological data, combined with early historic accounts, suggest a somewhat lower regional population than the late prehistoric period (Kintigh 1985). However, these towns were located in, and intensively used, only a small portion of the region, so the population densities remained high in the area that remained occupied. In contrast to the large, late 13th and early 14th century towns relying on runoff agriculture, in these protohistoric towns, irrigation would have provided much greater productive capacity in proximity to the towns. Relying on the Zuni River and large springs, the irrigated fields would have been buffered from variability in precipitation. In addition, their lower elevation greatly reduced their vulnerability to abbreviated growing seasons frequently experiences at higher altitudes. If the fields did not significantly degrade, and if the population was relatively stable, the vulnerability to environmental change and to social competition may have been reduced. However, the villages must have confronted new challenges associated with the management of the irrigation system.


Estimated Population
700
600
500
400
300
200
100
0
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
Years A.D.
HARP
OBAP
FLCM
MC

We might ask why it is that these favorable floodplain settings were not intensively utilized in earlier periods. Part of the answer may lie in changing floodplain hydrology (Dean 2007). However, it may well have been due to a lack of social infrastructure to integrate more concentrated populations and the existence of workable alternatives to relying on floodplain agriculture that did not require the social investments. Until the late AD 1300s, the Zuni area was relatively insular, with exchange evident only within the region. As the overall precipitation and temperature regime was regional in scale, exchange of food probably would not have been useful in buffering shortfalls due to major climatic events. However, after AD 1350 exchange across regional boundaries increased. Nonetheless, the distances to the nearest other occupied areas would have been large enough (more than 125 km to Acoma and nearly 200 km to Hopi) to call into question whether enough food could have been moved on foot to have a substantial impact.

Vulnerabilities and Transformation

Prior to the mid AD 1200s, the regional population seems to have maintained a low level of vulnerability to short-term environmental variability, to longer-term climatic change, and to major climatic events. People avoided this vulnerability through the small sizes of settlements (mostly no more than half a dozen households (Kintigh 1996), their short occupations (a few to perhaps 10 or 20 years (Thompson 2005), and the use of low-investment, runoff water-control technologies. These conditions suggest a historically (which is to say contextually) well-informed set of local responses to tradeoffs among agriculturally important environmental parameters. The social cost was high mobility, requiring investments in the maintenance of regional networks to facilitate movements, and attendant, repeated investments in new village construction.

From the late AD 1100s we see increasing aggregation, and by the late 1200s the entire population was highly aggregated. This aggregation would have necessitated a great increase in the average distance farmers had to travel to their fields and an increased social cost of integration. Despite the now-higher cost of mobility associated with the large towns, most villages were still shorted-lived (less than 20 years). However, aggregated settlements reliant on runoff agriculture evidently were not sufficiently robust to withstand the combination of vulnerabilities: social competition for attractive fields, and variability and potential declines in production due to the onset of long-term environmental degradation, including a dropping water table, a more variable climate, and extremely low precipitation from AD 1275-1300.

The increasing aggregation starting in the late 1100s would have entailed increasing investment in social infrastructure to deal with the greater levels of competition and conflict inherent in more aggregated social settings. In the 11th and early 12th centuries, the Zuni area was on the southern edge of the Chacoan regional system (Kantner and Kintigh 2006). Kintigh (1994) has argued the increased aggregation and organizational complexity we see at that time may have been a consequence of the mid 1100s breakup of this regional system into a number smaller polities competing with one another.

By the late 1300s regional settlement changed dramatically, with the movement of all villages to lower elevations and the shift to a reliance on irrigation. Movement to lower elevations greatly reduced vulnerability to short growing seasons. The use of water from reliable springs and rivers with large watersheds reduced vulnerability to spatially patchy rainfall that is associated with runoff fields. This shift was later aided by a rise in water table that ameliorated conditions for floodplain farming about AD 1450 (Dean 2007). The increased productivity per unit area of irrigation agriculture reduced competition for attractive fields. These post AD 1400 settlements were well spaced, perhaps also to minimize resource competition between them. In addition, social institutions developed in the 14th century, including the katsina religion (Adams 1992) or Southwestern Cult (Crown 1994), may have mitigated the social vulnerabilities of large towns with populations of several hundred people. Membership in these new social institutions crosscut the strong kinship orientation that must have dominated earlier institutions, greatly increasing social stability within larger population aggregates. As Kroeber observed in 1917 "The clans, the fraternities, the priesthoods, the kivas, in a measure the gaming parties, are all dividing agencies. If they coincided, the rifts in the social structure would be deep; by countering each other they cause segmentations which produce an almost marvelous complexity, but can never break the national entity apart (Kroeber 1917: 183, cited in Eggan 1972: 304)." These same integrative institutions may have established a framework on which effective management of an irrigation system could have been based.

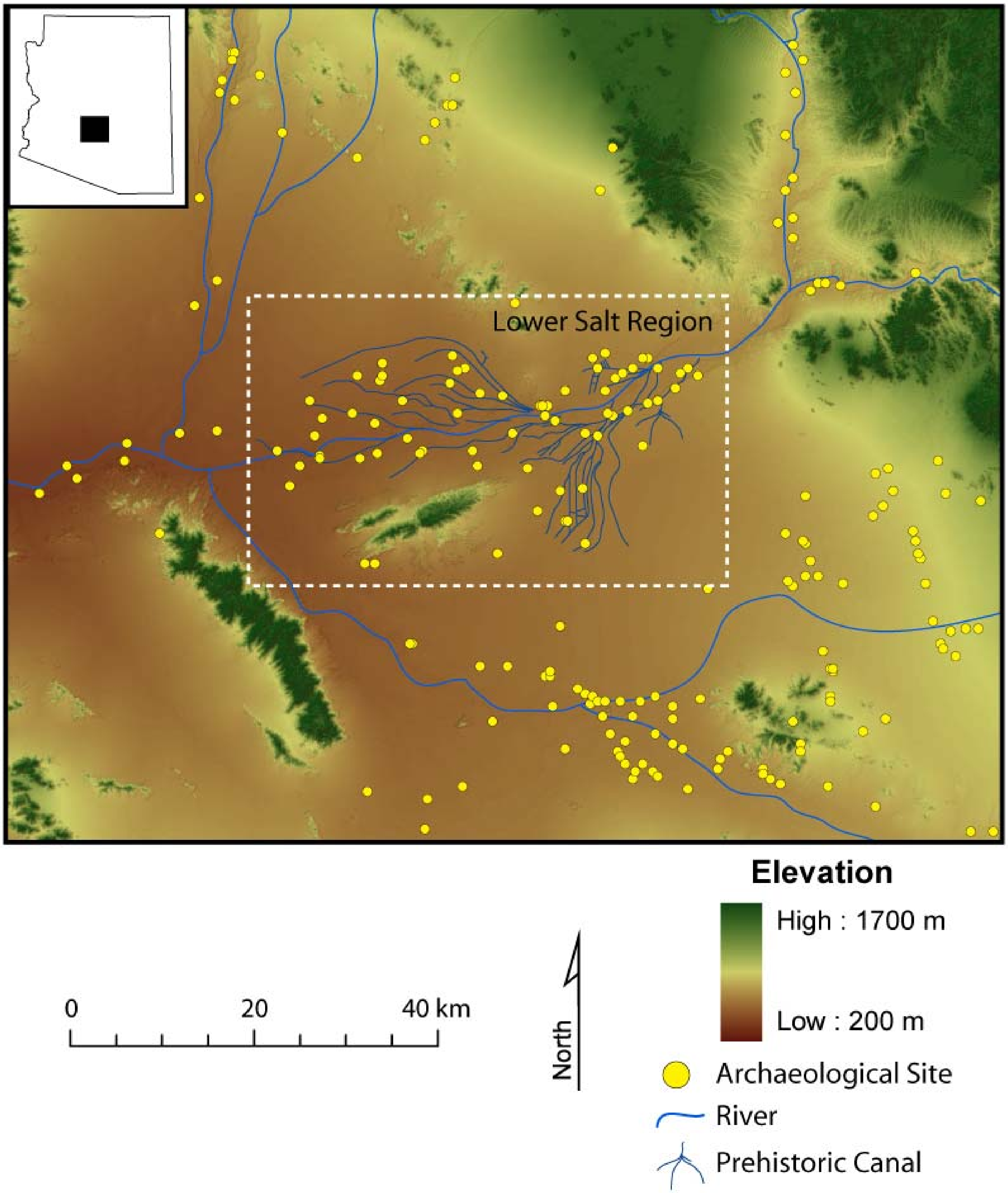
The social and population continuity in the Zuni case stand in contrast to the depopulation and reorganization of social institutions in the Mimbres case. Mimbres declines resulted from a complexity of factors. The insularity and settlement stability of Mimbres people allowed all three potential vulnerabilities to be realized. At Zuni, the strategies of changing land use frequently in concert with climate changes allowed an increasing population to remain in the region and social institutions to change gradually rather than collapse and reorganize as in the Mimbres case.

The Hohokam: Intensive Irrigation, Florescence, and Decline

The Hohokam region covers a broad area of southern Arizona; we focus on the people who lived along the lower Salt River in what is today the Phoenix metropolitan area (Figure 8). The prehistoric residents flourished in the valley for a millennium, occupying some of the largest, most densely packed, and longest-lived settlements in the ancient US Southwest. They attained a population size that some estimate at 30,000 (e.g., Earle and Doyel 2008), but whose presence declined to archaeological invisibility by the mid 15th century. Our research spans A.D. 800-1450, encompassing a major transformation, from cultural florescence and an integrated regional system of ceremony and exchange to a collapse of regional networks, and a long and steady slide of population and institutions towards total residential abandonment.

The lower Salt River valley was but one part of the Hohokam interaction sphere, which, at its height, encompassed 80,000 km^2; including the valley lowlands along the lower Salt, middle Gila, and Santa Cruz Rivers; upland territories to the north, south, and east; and low desert to the west and southwest. Beginning around A.D. 800, the regional network was integrated by shared ritual beliefs manifest by the playing of a ceremonial ballgame in large earthen courts. The regular gatherings of people from many places and a network that interconnected a wide variety of ecological zones made the ballgames conduits through which high volumes of exchange goods progressed. Wild resources, raw materials, and crafts flowed into the irrigated lowlands from the upland zones, and agricultural surpluses produced with irrigation moved outward from the well-watered valleys to the drier uplands (e.g., Abbott et al. 2007a; Doyel 1991; Howard 1993; Shackley 2005). By A.D. 1000, a ballcourt was present at about 190 villages (Marshall 2001; Wilcox et al. 1996).

The cultural florescence of shared rituals, widespread cooperation, and high-volume exchange across a vast region came to an abrupt halt around A.D. 1070, when the ballcourt network collapsed (Abbott 2006; Doelle and Wallace 1991; Doyel 2000). Large swaths of the upland zones became depopulated as emigrants streamed into the irrigation-based communities along the major rivers (Doelle et al. 1995; Doyel 1981; Teague 1984; Wilcox 1991). Regional exchange was significantly reduced (e.g., Crown 1991), and an intensive focus on local production for local consumption became the norm. Social fragmentation and territorialism took shape in such a way that social boundaries were coterminous with the irrigation infrastructure (Abbott 2000, 2003). Local political hierarchies emerged, which were associated with the construction and ceremonial use of platform mounds, whose exclusionary access was restricted by massive and towering compound walls (e.g., Gregory 1991). The local elites may have exerted a degree of ownership over the engineered landscape in order to extract from it a surplus to finance chiefly institutions (Abbott 2000; Earle and Doyel 2008). But their political power was largely ineffective for promoting the welfare of their constituents. Increased population pressure,



Lower Salt Region
Elevation
High : 1700 m
Low : 200 m
0
20
40 km
North
Archaeological Site
River
Prehistoric Canal

a greater emphasis on agriculture (Kwiatkowski 2003), and over exploitation of riparian resources (James 2003), led to environmental degradation, declining nutrition, increased disease, and rising mortality rates (Sheridan 2003; Van Gerven and Sheridan eds. 1994). Although occupation in the lower Salt River valley continued into the early 15^{th} century, the long and steady decline following the collapse of regional networks ultimately led to a total depopulation of a homeland that had been occupied for 70 generations.

Hohokam Agricultural system

The people of the Hohokam region are best known for their irrigation infrastructure – the largest network of canals in pre-Columbian North America. More than 500 km of gravity-fed channels sprawled across the Salt River valley floor in dendritic fashion, where perhaps as many as 650 km^2 were brought under cultivation with canal water (Gregory 1991:171; Masse 1981:408; Nicholas and Feinman 1989:199). The desert farmers organized themselves into multi-village irrigation cooperatives to manage their hydraulic works and cultivate crops of corn, beans, squash, and cotton. Each of the cooperatives maintained a set of main canals with a common headgate location, the smaller branch and distribution ditches that split from the main lines, and the agricultural fields planted along the canal routes. The warm desert temperatures, a generally reliable, predictable, and abundant supply of water in the Salt River, and the expansive acreage of irrigated fields probably provided for two harvests each year (Bohrer 1970). Regular surpluses of cultivated foods and cotton produced for exchange may have been the engine that powered the regional economy.

Realization of Potential Vulnerabilities

The advantages of the Hohokam irrigation-based economy are evident by the largest and densest populations in the prehistoric US Southwest, which were sustained for centuries. Ultimately, however, Hohokam society succumbed to wrenching change, eventually leading to total depopulation of the lower Salt River valley. Production at multi-village irrigation cooperatives, situated along the Salt River, was a key component of a much larger regional economy that circulated high volumes of goods, including basic necessities like utilitarian pottery vessels, across the region. As such, this broad-scale economy was vulnerable not only to direct impacts to irrigation management but also to changing conditions that affected production in other sectors, and pressures on the social networks through which goods were distributed across the region.

As described by Anderies (2006; Anderies et al. 2004), robustness in one realm is often achieved at the cost of vulnerability in another. In the Hohokam case, the large-scale irrigation technology and its great capacity to supply agricultural surpluses was highly robust to local fluctuations in rainfall, which contributed to the creation of a regional scale economy. But it did so with increased vulnerability to social and ecological perturbations at specific localities, which because of the crosscutting interdependencies could be felt across the region. Again, we examine three potential vulnerabilities and their influences on transformations in the Hohokam: a) the effects of rare climate conditions, b) the effects of place focus on degradation and depletion of resources, and c) the effects of increased capacity to support local population on eventual resource stress especially in dry years.

a) Potential impacts of rare climate conditions (shock frequency trade-off): Annual discharge of the Salt River is determined by winter precipitation in the upper reaches of the watershed in the White Mountains (Graybill 1989). Flow increases steadily from November to March, reaching a maximum in most years coeval with a critical irrigation interval pertaining to planting of the first corn crop. The river then typically slows to its lowest level in July, coincident with the planting of the second crop. The intensity of the spring floods probably destroyed diversion weirs and headgates in most years, a circumstance dealt with routinely by Hohokam farmers (e.g., Hunt et al. 2005). Larger floods, however, could bury the upper sections of canals in sediment, requiring considerable repair and possibly the loss of the first crop. Variation in the water amounts during the July planting almost certainly affected the extent to which a surplus was produced from the second crop.

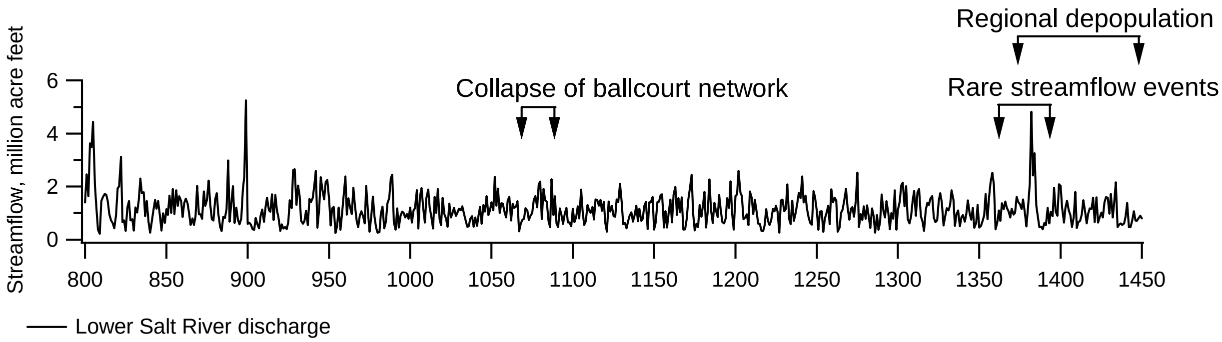
At least 1,000 years of irrigated agriculture along the Salt suggests the effectiveness of strategies such as storage, food sharing, and exchange to buffer against food shortfalls when climate or other events diminished agricultural production. Extreme climate events in the late 1300s, however, came at a time when population and associated food requirements were at their peak. Between A.D. 1356 and 1384, discharge patterns occurred that had not been experienced in over 500 years (Figure 9). Extreme events during this period included two very high annual flows preceded and followed by low flows that likely magnified the geomorphic effect of these events on the stream channel and associated canal intakes (Graybill et al. 2006:117). These events could have contributed to the long-term slide towards total abandonment.

Earlier climatic events in localities beyond the lower Salt River valley may be more directly implicated in the collapse of the ballcourt network and the regional economy. For instance, some theorists conjecture that down-cutting in the middle Gila riverbed during the 11th century may have left some canal intakes high and dry, significantly reducing the agricultural outputs along the middle Gila River and the stability of the entire regional economy (Waters and Ravesloot 2000). The efficiencies of complementary production from one ecological setting to the next in the regional system can raise the total productive capacity, but the interdependencies can amplify the impacts of local changes as they are felt throughout the region.

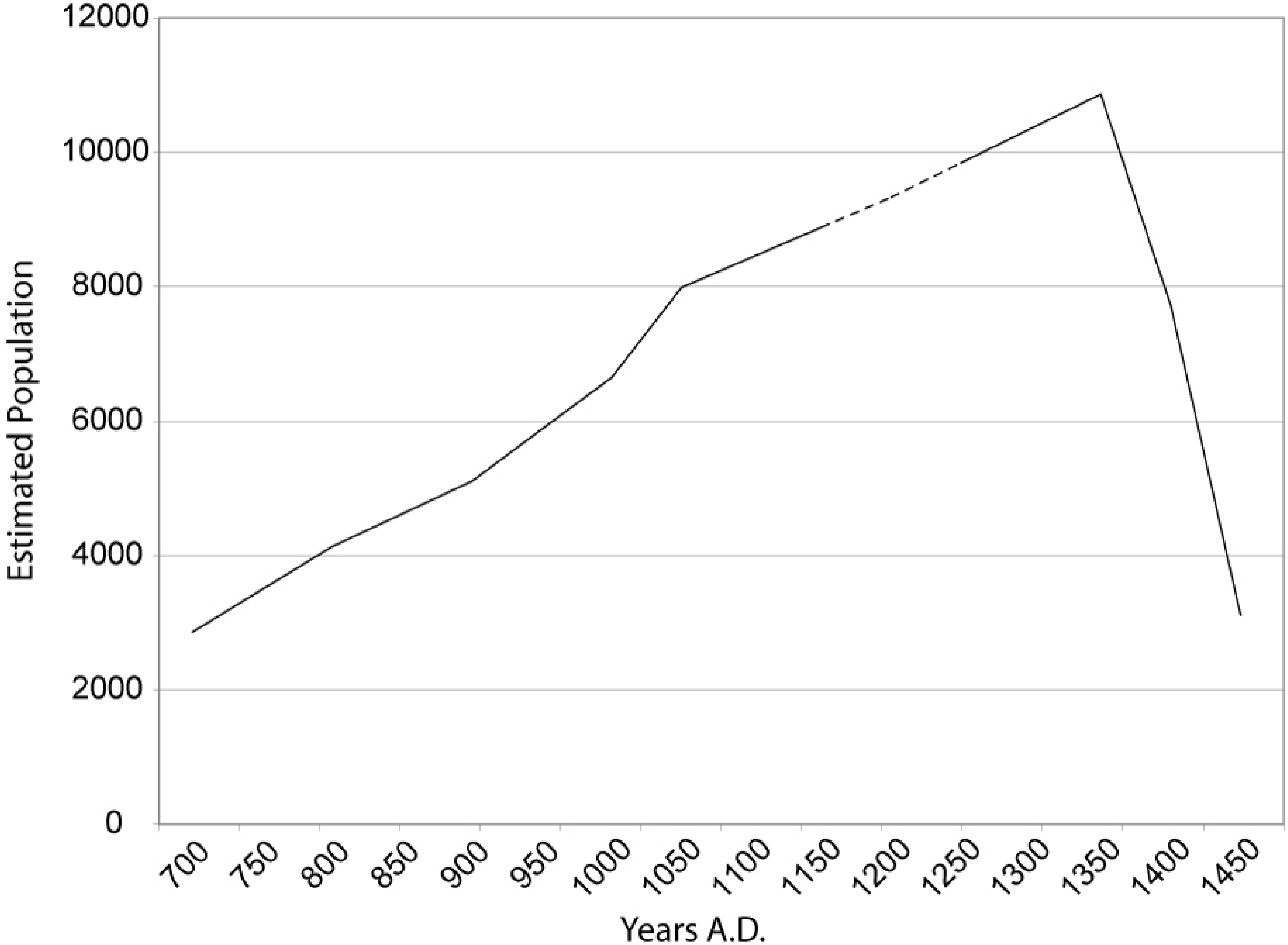
b) ***Residential stability and the potential for depletion of resources (local focus and reduced response capacity)***: Cereal growers worldwide typically rely on their cereal crops for about half of their caloric intake (Cordain 1999; Haard et al. 1999). Diet-related evidence indicates that the Salt River inhabitants, who continuously occupied villages for a millennium, supplemented their harvests of corn with bean and squash crops, and depended on gathering and hunting local wild resources (e.g., Gasser and Kwiatkowski 1991; Szuter 1991). The regional economy in which they participated also supplied hunted and gathered resources from various ecological zones, and, with the expansion of the regional networks over time, it is likely that the irrigation communities in the lowlands became ever more dependent on non-local comestibles until the regional collapse. Prior to the collapse around A.D. 1070, there were no signs of environmental degradation along the Salt River. But immediately following that time, the northern uplands overlooking the lower Salt River valley became depopulated, while settlements along the river rapidly swelled with migrants. The impacts to the local wild resource stock were substantial with severe health consequences for the Salt River populations (James 2003; Kwiatkowski 2003; Sheridan 2003; Van Gerven and Sheridan 1994). Iron-deficiency anemia became rampant (Van Gerven and Sheridan 1994), probably related to a disruption of large-game supplies from the upland zone (Abbott 2003). Greater emphasis was placed on irrigated crops with a resultant narrowing of the diet (Kwiatkowski 2003), which, unfortunately, happened just prior to the change to a more chaotic streamflow regime in the Salt River. The Salt River Hohokam invested heavily in their irrigation infrastructure to supply a regional market on which they, in turn, depended for vital resources. The interdependencies succeeded in building an efficient and productive regional economy but at the risk of local perturbations whose effects could cascade across the system.

c) ***Potential for population growth and demand on food supply (slow-fast variable trade-off)***: Steady population growth along the Salt River probably characterized the period between A.D. 700 and 1350, with a rapid decline thereafter (Figure 10). The sustained agricultural success, however, may have encouraged a substantial expansion of the hydraulic infrastructure sometime around A.D. 1000, at the height of the regional economy. A major irrigation complex, named the “Lehi Canal System,” was built upstream of the other irrigation cooperatives on the

Figure 9 Stream flow discharge of the Lower Salt River in the Hohokam Region.



Streamflow reconstruction developed by Graybill et al. (1989, 2006) and the Laboratory of Tree-ring Research, University of Arizona


12000
10000
8000
6000
4000
2000
0
Estimated Population
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
Years A.D.

river (Howard 1987), possibly by a migrant group from the middle Gila River valley to the south (Abbott 1995). The establishment of several new ballcourt villages and the addition of hundreds of irrigated hectares put new pressures on the water supply, which may have become a limiting resource at that time (Howard 1993). Diversion of the river flows by the Lehi farmers may have undercut the capacity of some downstream irrigation cooperatives to grow a surplus of corn and cotton for trade. In effect, the productive output in the valley as a whole may have reached a maximum, while expanding local populations consumed their share and left a diminishing proportion of the total output for exchange with populations elsewhere in the region.

Vulnerabilities and Transformation

By investing in large-scale irrigation technology, the Hohokam farmers in the lower Salt River valley assured themselves of a goodly supply of cultivated resources. At the same time, their infrastructure investments densely concentrated a large population in a single place, putting their local environment at risk for depletion and degradation. The Salt River inhabitants initially avoided that vulnerability by participating in a vast network of exchange organized around widespread sharing of religious beliefs and periodic ceremonial festivities at ballcourt villages throughout the region. Fostered by a reliable, predictable, and abundant streamflow regime in the Salt River, the irrigation works were built to supply a surplus production of food crops and cotton to a regionally integrated economy. The efficiencies of local specialization and the integration of diverse ecological zones via the ballcourt rituals underpinned webs of “reliable dependencies,” but at the risk of hypercoherence, whereby perturbations at a local level were felt throughout the region. When interconnections are too strong and too critical, local changes, such as rising imbalances between supply and demand, sociopolitical strife that disrupts the movement of goods, and impairments to production capacities, can cascade through the regional networks, causing regional-scale social, political, and economic transformation.

Why florescence suddenly changed to decline around A. D. 1070 remains a key issue for research, although several ideas include: overexpansion of the Salt River infrastructure with the construction of the Lehi Canal System (Howard 1993); an unusual down-cutting event in the Gila River that entrenched the channel, dropping the water level below the reach of some canal diversions (Waters and Ravesloot 2000); and political unrest and hostilities at the northern margins of the Hohokam territory that pushed inhabitants out of vulnerable upland areas into the densely occupied lowland communities (Wilcox et al. 2001). Each of these possible events could have disrupted and fragmented the regional economy.

By severing connections to the larger networks after A.D. 1070 and reducing their exposure to regional-scale vulnerabilities, the irrigation cooperatives along the Salt River insulated themselves from external pressures but assumed the risks of going it alone following the collapse of the regional ballcourt network. Local political hierarchies emerged in each of the irrigation cooperatives, possibly taking command of the hydraulic infrastructure, supervising the construction of platform mounds for exclusionary ceremonies, and advocating the social boundaries coterminous with the cooperative’s irrigation works (Abbott 2000; Abbott et al. 2006; Earle and Doyel 2008). Under their leadership, agricultural production for local consumption was intensified (Kwiatkowski 2003), presumably to supplement for the loss of wild plant foods and game that had previously been acquired via transactions with external populations as well as to feed newly arrived immigrants who apparently exercised their kinship options to join the irrigation communities (Abbott and Foster 2003). The result was a narrowing of the diet, local habitat imbalances leading to environmental degradation, poor health, and increased mortality (James 2003; Van Gerven and Sheridan eds. 1994). Along the Salt River after A.D. 1070, cultural fluorescence gave way to a protracted and steady decline until the last Hohokam family left the valley.

The Hohokam case contrasts with the Mimbres and Zuni in the scale of population and investment in water control infrastructure, among other dimensions. But simple scale differences do not account for the differences in the trajectory of demographic and social change. For centuries people in the Hohokam region managed with their population increases and settlement stability, in part because of the advantage offered by their broad regional network through which people and resources were regularly moved. The Mimbres lack of such a network in the 12th century contributed to their decline. And among the Hohokam, as Abbott has argued, the collapse of this important regional network began their slow decline. All of the potential vulnerabilities, on which we focused for this paper, came together to result in the most dramatic population decline in the prehistory of the US Southwest.

Lessons

For arid-land farmers, physical infrastructure that captures or directs water for agriculture ameliorates short-term temporal and spatial variability in precipitation and improves productivity. In our cases, it made agriculture possible in many places where it would not otherwise have been. But, water management infrastructure also creates vulnerabilities to various conditions, even in the small-scale systems: the effects of rare climate conditions and the condition of the infrastructure, the effects of place focus on degradation and depletion of resources, and the effects of increased capacity to support local population on eventual resource stress especially in dry years. As we have emphasized, all of these are *potential* vulnerabilities; their effects are context dependent. If population does not increase as a result of improved productivity, for example, food stress may not emerge as a vulnerability. Our examination of context over long time sequences addresses the variety of social and behavioral practices associated with physical infrastructure that counteract some potential vulnerabilities or give rise to others. We do not suggest that potential vulnerabilities necessarily were recognized by the people living in these societies or that their social and behavioral practices necessarily were designed or adopted to reduce those vulnerabilities; that's a different paper. We do suggest that generalizing about vulnerabilities is not productive without an understanding of the social context of a case and a long-term view of how resilience and vulnerability interact.

In the Hohokam case, the physical infrastructure of water control – an extensive canal network -- was sustained for over a millennium. Through many periods of low and high precipitation, the infrastructure remained in place. Although people were "place-focused," for centuries they acquired a wide array of resources through an extensive, pan-regional exchange network, which also provided a social environment conducive to maintaining their extensive canal network. Once that network was replaced with balkanized local networks, various resources were no longer available and the social relations that supported the canal systems were changed. With these changes, the potential vulnerabilities were realized; people suffered and institutions collapsed.

In the Mimbres case, investments in infrastructure and a focus on floodplain farming eventually contributed to a place-focused residential pattern. This sedentism, one of the vulnerabilities of investments in physical infrastructure, resulted in resource depletion. The social institutions that supported village life were discontinued, but unlike the Hohokam case, we see no suffering or major institutional collapse. People had maintained a diversity of field areas, which became their new settlements as they reorganized within their homeland. Vulnerabilities to resource depletion and low precipitation led to reorganization, but practices of managing fields in diverse settings may have tempered the changes brought on by those vulnerabilities.

Finally, the Zuni case illustrates how social and physical changes, together, kept potential vulnerabilities from being realized. The water delivery infrastructure in the Zuni region was much smaller scale, and more dynamic than that in the Hohokam region; farming strategies were altered with shifts in climate and population. In addition, unlike the people of the Mimbres

Classic Period, Zuni villagers did not become "place-focused" even with considerable investments in physical infrastructure (villages and fields) until the end of the prehistoric sequence when they had developed social mechanisms that reduced factionalism. This cultural group continues into the present living in the Zuni region.

We are well aware that the fragmentary nature of the archaeological record constrains the detail with which we can reconstruct the social processes that underlie the resilience properties of social-ecological systems. However, archaeology allows us to examine the dynamics of SES's on temporal and spatial scales that are otherwise unattainable. By augmenting the archaeological record with ethnographic, historical and other relevant data, we can develop hypotheses concerning the interactions between social and physical infrastructure and the environment that supports them.

Our comparison of the Mimbres, Zuni, and Hohokam cases illustrates three types of potential resilience-vulnerability trade-offs involving different temporal and spatial scales: 1) annual versus multi-decadal frequency of environmental variation, 2) local versus regional scale of economic organization, and 3) immediate versus delayed change of key variables affected by human decisions. For example, humans may act to enhance robustness of their physiological state on a daily or monthly basis, responding to variation in the productivity of their resources as they experience them throughout an annual cycle. Their very success may lead to increased vulnerability to processes that change much more slowly -- population growth or soil depletion, or rainfall variation with multi-decadal frequencies (100-year floods).

The Hohokam in the Salt River Valley invested in massive local infrastructure to suppress variation at annual frequencies. However, this success may have generated vulnerabilities to population growth that occurred on a generational time-scale and led to the depletion of local resources. In response, the Hohokam developed social infrastructure at the regional scale – elaborate trade networks—that enabled them to successfully deal with local scale, high frequency shocks at the expense of low frequency, social shocks at a regional scale. However, regional disruptions may have led to population movement into the Salt River Valley, re-exposing and exacerbating the vulnerability of local resources. This cascade of vulnerabilities resulted in the most striking and catastrophic transformation of the three cases.

These potential vulnerabilities played out differently in the Mimbres and Zuni cases. Through most of the period considered here, population density in the Zuni area may have remained low enough, and movement frequent enough, that the inhabitants did not expose themselves to serious resource vulnerabilities at local spatial scales. However, increased social and resource vulnerabilities at a local scale must have accompanied the initial regional scale social shift to highly aggregated settlements. These vulnerabilities were mitigated by frequent movement—and probably the fissioning and recombining of social groups—until, just prior to the historic period, the social and physical infrastructure were developed to maintain concentrated populations that were highly place based.

In the Mimbres case, people became focused on local resources but in a different sequence from the Hohokam. Rather than beginning with a local focus and expanding their scale, they may have had a regional-scale focus that eventually shifted to a local focus. And rather than responding to a local crisis with further local intensification as the Hohokam did, the Mimbres people may have returned to a regional scale focus when they reorganized after the depopulation of villages, avoiding a transformation of the magnitude of the Hohokam.

These cases highlight an important message: as societies attempt to cope with variation and vulnerabilities at particular scales and in particular domains, they must be keenly aware of the vulnerabilities they are generating at other scales and in other domains. Lack of such awareness is a recipe for a costly and likely unpleasant transformation. Armed with this awareness, people can better weigh the implications of their decisions, and attempt to build general resilience to respond if and when potential vulnerabilities are realized.

List of Figures

Footnotes

[1] Tree-ring precipitation reconstruction developed by Grissino-Mayer, Baisan, and Swetnam (1997). Funding for the reconstruction provided by the Legacy Program, Directorate of the Environment, Natural Resources Division, Fort Bliss, Texas. Grissino-Mayer is affiliated with the University of Tennessee. Baisan and Swetnam are affiliated with the Laboratory of Tree-Ring Research at the University of Arizona.

Periods of extremely low precipitation identified by Ingram (2008) using a nine-year interval running average throughout the duration of the tree-ring precipitation reconstruction (e.g. A.D. 622 to 1994). Extreme lows defined as those intervals in the lowest quartile and decile of the distribution of all nine-year intervals in the reconstruction.

[2] Population estimates for the Mimbres case are based on a large settlement database compiled as part of the Long Term Vulnerability and Transformation Project. The settlement database includes all sites in major full coverage surveys across the region as well as all known large sites (e.g., sites with approximately 30 rooms or more). The population estimates were produced by placing sites in each time period into a number of site size classes based on the best known and recorded components in the database for a particular time period. Sites for which less information was available were placed in size classes based on the available data, and were assigned the mean room count of sites in that size class. Following Nelson and Schollmeyer (2003), every 2.5 rooms were assumed to represent one nuclear family household of approximately four individuals. Room use life estimates were assumed to be roughly 50 years for the purposes of this analysis. The database is likely missing a large proportion of sites dating to the earliest time periods (Early and Late Pithouse Periods: AD 400-1000). Thus, population estimates for the earliest periods were defined based on the rates of growth in the best known portions of the region (Blake et al. 1986).

Population estimates for the Zuni case were not calculated for the region as a whole. Instead, four large full coverage survey areas were used to illustrate the magnitude of changes occurring through time in specific places. These surveys consist of the Heshotauthla Archaeological

Research Project (Kintigh et al. 2004), the Ojo Bonito Archaeology Project (Kintigh 2007), the Fence Lake Coal Mine Survey (Hogan 1985), and the Miller Canyon Archaeological Survey (Kintigh 1980). Sites were placed into temporal categories using the proportions of well dated ceramic complexes (following Kintigh et al. 2004). Room counts assigned to each temporal interval were converted into population estimates assuming 2 people per masonry room. Population estimates were then adjusted to account for the length of each interval assuming a site use life of approximately 25 years.

Population estimates for the Hohokam region are primarily based on previous work by Doelle (1995, 2000). Doelle estimated population by placing all large sites across the region into a number of site size classes, and defining a momentary population estimate for each size class based on the best known examples in each category. Doelle then used the existing information from archaeological surveys across the region to estimate roughly what proportion of the sites in a given time period are likely known. This information was used to create conversion factors that attempt to account for sites missing from the database. In this study, Doelle's original procedures are used, but new information on specific sites and time periods has also been incorporated into the database altering the previously published estimates. The dotted portion of the line in Figure XX represents a time period for which we have little data. For the purposes of this study, we assume that population increased gradually during this time to the levels that we have estimated for the better known period at around AD 1200.

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