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Endogenous change: on cooperation and water availability in two ancient societies

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Abstract. We propose and test the theory of endogenous change in societal institutions based on historical reconstructions of two ancient civilizations, the Indus and Hohokam, in two water-scarce basins, the Indus Basin in the Indian subcontinent and the lower Colorado Basin in the southwestern United States. In our reconstructions, institutions are approximated by the scale of "cooperation", be it in the form of the extent of trade, sophisticated irrigation networks, a central state or a loosely held state with a common cultural identity. We study changes in institutions brought about by changes in factors like rainfall, population density, and land-use-induced water resource availability, in a proximate manner. These factors either change naturally or are changed by humans; in either case we contend that the changes affect the stability of cooperative structures over time. We relate the quantitative dimensions of water access by ancient populations to the co-evolution of water access and the socioeconomic and sociopolitical organizations. In doing so, we do not claim that water manipulation was the single most significant factor in stimulating social development and complexity – this would be highly reductionist. Nonetheless, we provide a discussion with the aim to enhance our understanding of the complexity of coupled human–hydrological systems. We find that scarcity triggered more complex cooperative arrangements in both Indus and Hohokam societies.

1 Introduction

There are a number of studies that discuss how societies have interacted with their part of the planet's limited and now diminished resource base, and provide insights into how these societies sustained themselves and their resources (Greif and Laitin, 2004; Costanza et al., 2011; Fisher et al., 2009; Janssen and Anderies, 2007; Lansing, 2003; Mithen, 2012). Following their lead, we discuss qualitative and, where possible, quantitative dimensions of water access and control by ancient populations in this paper. We aim to shed light on the kind and degree of socioeconomic and sociopolitical organization in the context of hydrological change that influenced the human past.

A focus on water does not mean that we claim that water manipulation was the single most significant factor in stimulating social development and complexity – clearly this has been shown as highly reductionist, even misleading. Nevertheless, water remains a vital resource for human survival and a resource that many societies have sought to control. It requires major energy outlays to command and significant infrastructural advances to accommodate population growth. When we can articulate how past water systems were managed, we are in a position to evaluate aspects of their associated societal institutions. These institutions "have slowly evolved on the highly variable landscapes from which people make a living. Even under appreciable stress, water management systems tend to persevere because of their adaptability. This aspect of water management receives less attention because it is less spectacular than the origin or collapse of a system. Nevertheless, societal maintenance and sustainability deserve greater scrutiny in our rapidly changing world." (Scarborough, 2003; p. 3–4).

Apart from being a field of study in itself, archaeological studies on water – and natural resources in general – provide the longue durée necessary to assess the robustness of a coupled human–water system. Learning how resilient a system has been to hydroclimatic variability or change – something that archaeological records may already provide – become

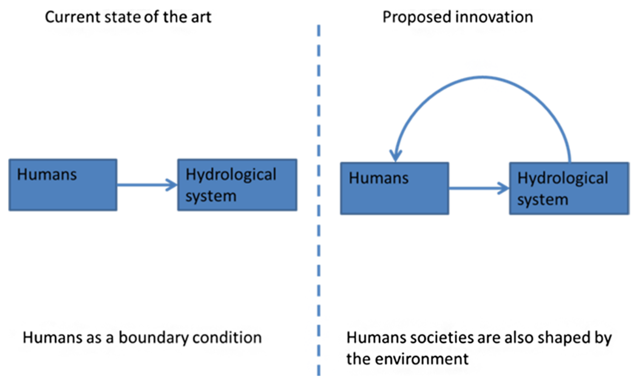

Fig. 1. An illustration of feedbacks between hydrological systems and human societies.

the principal means to identifying a comprehensive notion of "sustainability". In most current debates on environmental change, responses of human societies to said change, in terms of actions and institutions, have been considered as fixed boundary conditions for hydrological processes or as parameters describing the dynamics of hydrological change. We argue that a dynamic representation of change with feedbacks between hydrology and humans is a key requirement when studying societal change, reminiscent of processual ecological anthropology (Orlove, 1980). Once established, such studies would provide a framework to incorporate human decision-making and corresponding feedbacks in the broader dynamics of hydrological change. Figure 1 illustrates the proposed idea.

In this paper, we build upon the theory of endogenous institutional change proposed by Greif and Laitin (2004) for water-scarce regions. As the available data set is limited for a quantitative test of the theory of endogenous change in a context of water scarcity, the aim of our paper is to find qualitative evidence for the endogenous change (i.e., change that is brought about by the intrinsic dynamics of a system). We are interested in (1) those conditions under which cooperative patterns (i.e., patterns of how individuals or constituents of a system cooperate with each other) emerge or collapse as suggested by the theory of endogenous change and (2) linking that to quantitative evidence of water scarcity. In this paper, we will study the emergence and/or disappearance of patterns of cooperation in human societies at the scale of a civilization/tradition (we will use the words interchangeably), from its genesis to dispersal.

To put the theory of endogenous change to the test, we have selected two case studies of two civilizations that flourished and dispersed in principal mid- to late Holocene in two dry land areas of the world: the Indus Basin on the Indian subcontinent, and the Sonoran Desert in the present-day USA. Water availability and control in the Holocene societies in these areas played a dominant role, and both have been well studied both by paleoclimatologists and ecological anthropologists/archeologists alike (as we discuss in the following). Based on available data, we develop proxy data on water availability to study how this might have affected the socio-economic organization of these societies. We view the organization of such societies as resulting from individuals cooperating within a society, and analyze the evolution of the societies in terms of how water availability might have shaped societal organization. Our analysis provides an explanation for the rise and dispersal of Indus Valley Tradition under increasing water stress. For the Hohokam case, we argue that it was increased variability in the occurrence of wet and dry periods coupled with population growth that might have amplified the scarcity conditions and triggered change.

However, let us first focus on the theory of endogenous change itself, before we discuss in much more detail how our two ancient societies can be understood from such a perspective. We end the paper with a discussion of the implications of our findings for our approach for further study of feedbacks between societies and their hydrology.

2 Endogenous change and water

The theory of endogenous institutional change proposes a theory for the basic question of why institutions change. Institutions are defined as systems of organization, and rules that influence individuals' decisions of resource use (Greif and Laitin, 2004). Since we view the organization of individuals as resulting from how they cooperate with each other, we view changes in institutions as changes in the manner of how individuals cooperate amongst themselves. A change in how individuals within a society cooperate in our case is hypothesized to be driven by water resource availability that, in turn, may be driven by human actions. The term endogenous emphasizes that institutional changes do not occur as a direct result of changes in water resource availability, but indirectly via changes in the structure of cooperation between individuals.

Our use of these general notions of endogenous change is based on the assumption that complex societies cannot rise under resource constraints or uncertainty (such as water scarcity) unless societies efficiently allocate and use resources. Technological innovation provides higher production per unit input and sustains a "positive" population growth rate, even under increasing scarcity conditions (see Pande et al., 2013). Another way to deal with scarcity may be a larger scale of cooperation, be it in the form of regional infrastructural development, trade linkages or emergence of a state with a strong central authority, allowing societies to use resources more efficiently and thus induce faster growth in technological innovation (see for example a discussion on the link between rate of technological innovation and the size of markets in Romer, 1990). However, certain conditions need to be met for larger-scale cooperation on allocation of resources within a basin. These conditions depend on the

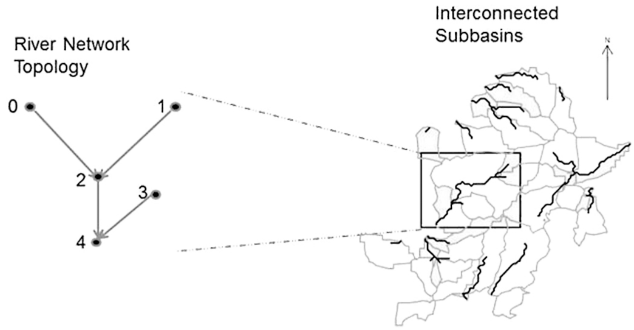

Fig. 2. Conceptualization of a river basin and a river network from Pande et al. (2011). Only hydrologic connectivity is conceptualized.

spatial or statistical pattern of scarcity conditions (see Ambec and Sprumont, 2002; Pande and McKee, 2007) and the timescales at which human actions are undertaken (Ertsen et al., 2013).

We propose that water scarcity and societal development may be related, in the sense that increased cooperation may be an answer to increased water scarcity. Increasing scarcity conditions or increasing variability of wet and dry periods exacts costs on a society to which it answers. We do not suggest a linear relationship (and hence we do not suggest a correlation) between the evolution of societies and scarcity (or increased variability of) conditions. Our discussion below suggests that a society can mature under diminishing water resource availability (increasing scarcity conditions) at regional scale, provided the spatial or statistical pattern is favorable for regional-scale cooperation. The spatial and/or statistical pattern of scarcity conditions is a crucial element in the feedbacks in this relationship.

In order to study the scarcity patterns and their influence, we conceptualize a collection of interconnected sub-basins where each sub-basin represents an agent who engages in water-intensive production activities (Pande et al., 2011; Fig. 2). Connectivity between any two sub-basins is either due to the flows between them (hydrological) or due to trade or other forms of interaction (economic). The organization of agents at basin scale is an appropriate unit of analysis in a context of hydrologic change, due to the hydrological and hydraulic connectivity between agents that is internalized at that scale (Pande et al., 2011). Such connectivity is affected by agents' actions, which are partially the result of institutional rules and constrain future actions of the agents. Such feedbacks also influence future change in the hydrological state of the basin.

Studying change in the context of an evolution of rules requires the understanding of processes that generate such rules and that select and/or retain rules based on certain criteria, such as resource use efficiency (Ostrom and Basurto, 2011; see also Thelen, 1999; Steinmo, 2008; Vadya and McCay, 1975). However, such processes of change have often been criticized. The units of analysis in such processes of change are often ambiguous. The dynamics driven by optimality principles, such as the survival of the fittest or maximizing energetic efficiency and productivity, may be applicable to individuals but perhaps not to the system as a whole (Vayda and McCay, 1975). As such, there is a need to develop theories that can describe system properties, group formation or dissolution and corresponding processes of decision-making in terms of the attributes of their component individuals (Boissevain, 1968; Hall, 2009). Such theories can provide a framework to understand and predict socio-hydrological systems, in particular in the context of change (Sivapalan et al., 2012). This also corresponds closely to Dopfer et al.'s (2004) micro-meso-macro architecture, with the micro-domain referring to the individuals that execute rules, the meso-domain referring to the scale at which the process of rule change occurs, and the macro-domain referring to the population of systems under change.

In our analysis, the presence or absence of (evidence for) cooperation at any spatial scale is the proxy for the "organization" of individuals, while the choices that individuals make regarding land use and water extractions are conditioned by the nature of coalitions formed. Cooperation organizes individuals with rules that condition their choices of resource use. It can be in the form of upstream–downstream trade, sophisticated irrigation networks, a hierarchical state or a loosely held state with a common cultural identity.

We comparatively assess two basins at basin ("meso") scale. The sub-basins within the larger basin then represent the micro-domain in which decisions on the use of water are made. Recently Pande (2013) demonstrated that heterogeneity in local scarcity conditions of agents are important determinants of the scale of cooperation at basin scale. The effects of such heterogeneities on cooperative water allocation have also been found at field scale (see e.g., Komakech et al., 2012). In the case of water-stressed regions, the river network topology strongly determines the interaction between sub-basins and as such institutional development; upstream agents often value water differently from the downstream ones. The pattern of different values water has for different agents from upstream to downstream is key for a basin-scale cooperative structure (not) to emerge (Pande, 2013). Agents change variables like population, land cover and production activities, which then lead to changed local scarcity conditions relative to other agents. This then results in new conditions, which determine how agents cooperate amongst themselves. A similar effect is to be expected from the changing variability of scarcity conditions. Just as increasing scarcity exacts costs on a society, increased variability in scarcity conditions also exacts costs, even if average conditions are not water scarce. Appendix 1 exemplifies it further. The interplay between agents and the variables, such as population, land cover and production activities, result in different patterns of cooperation over time, which in turn determines the co-evolution path of water use and institutions by determining the conditions for cooperation in the future (Fig. 3a).

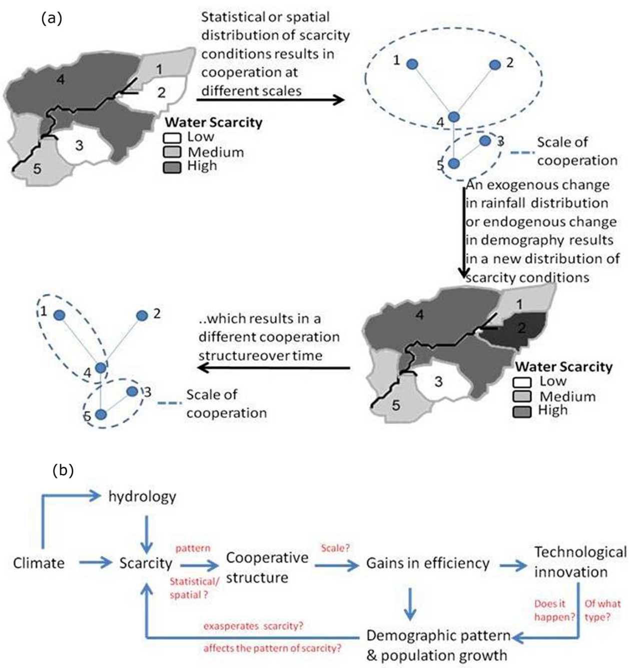

Fig. 3. Illustrations of the theory of endogenous change.

We use the reconstructions of our two societies to test the regularities predicted by the theory. Instead of suggesting a linear relationship between scarcity and evolution of societies, our approach advocates a much more general relationship; it does not preclude a linear relationship either. Emergence or dissolution of cooperative structures plays a dominant role in the evolution of societies, which in turn depends not only on exogenous factors such as climate and hydrology, but also on "endogenous" factors such as organization and growth of the society (which is again partially a consequence of cooperative structures and technological innovations engendered by past scarcity conditions). Thus, the theory that we present considers humans as carriers of feedbacks on future scarcity conditions, and hence future organization of human societies (Fig. 3b). We qualitatively test the regularities predicted by the theory (the causality) based on the limited data sets that we have for the case studies.

Any strategy a society develops to deal with climate depends on past and present technological innovations, which in turn not only depend on the need of a society to "act" (not react), but also on whether the society is capable to do so (Fig. 3b). While a 'resource-constrained' society may ideally want to act on many pressing issues, the issues that it ends up acting on depend on a complex mix of institutions and technological innovations. We suggest that spatial distribution of resource scarcity or uncertainty in resource availability plays a crucial role.

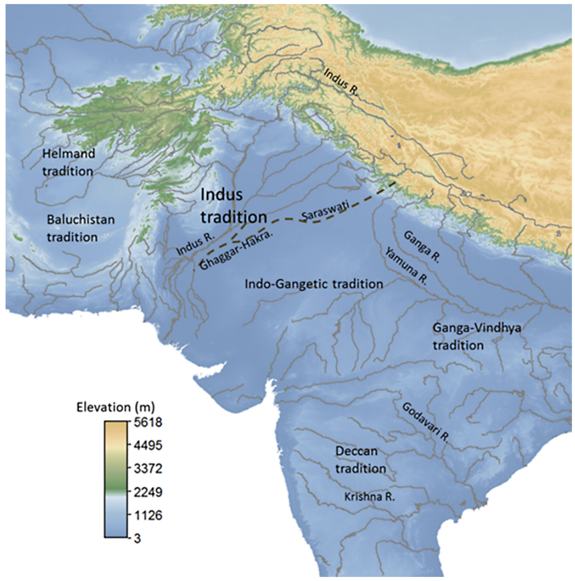

Fig. 4. The traditions of the Indian subcontinent between 5000 and 2000 BP (after Kenoyer, 2011, 2006).

3 Indus Valley Tradition (Harappan Civilization/Tradition)

Two urban civilizations were present in the Indian subcontinent between 5000 and 2000 BP (Fig. 4); the first was the Indus Civilization, or the Harappan Phase of the Indus Tradition, dating from 2600 to 1900 BC (4600–2900 BP). The second was the Early Historic urbanism that began around 600 BC (2600 BP). The urban developments of the Early Historic Period began with the continuation of urbanism in the northern Indus Valley and the spread of urbanism into the Ganga–Yamuna Doab (Erdosy, 1995; Kenoyer, 1995), central and southern India (Allchin, 1995b).

The early settlements in the Indus Valley began to appear around 9000 BP in Mehrgarh, the western part of the Indus Valley (Kenoyer, 2011). This was the transition of human societies from foraging to early food production and domestication of animals by settling along the fertile banks of the Indus River and its tributaries. However, during this early Food Producing Era, continuing up to 7500 BP (Kenoyer, 2011, 2006), the population engaged both in foraging and food production (Fig. 5a). Thereafter the area witnessed population growth and an increase in the number of settlements (Fig. 9) and the population centers started to interact (Kenoyer, 2006; see also MacDonald, 2011; Madella and Fuller, 2006; Kenoyer, 2001). The interaction network spanned from Amu Darya in Central Asia to Dholavira in present-day Kutch, Gujarat (Fig. 5b). The interaction network evolved over time, possibly as a result of increasing specialization due to spatial heterogeneity in resource availability and population pressure. It marked the beginning of the Early Harappan Phase from 7500 to 4600 BP (Kenoyer,

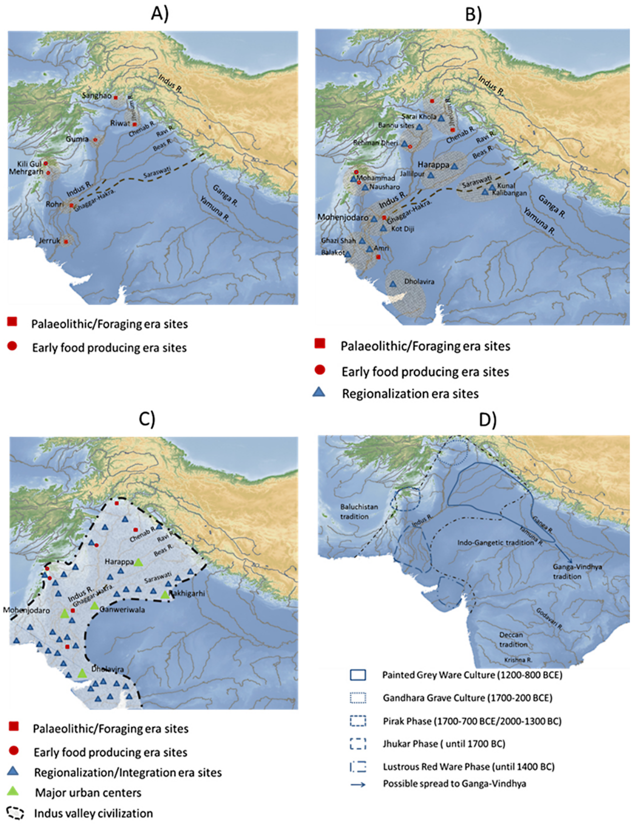

Fig. 5. The chronology of the Indus Valley Tradition. Compiled from Kenoyer (2008, 2011).

2011, 2006), in which the identity of Harappan Tradition began to regionalize (Fig. 5b). The city of Harappa served as major hub, linking settlements in the north and the northwest of the Indus Basin to the south. Between 4600 and 3900 BP, settlements in Harappa in the north and Mohanjo-daro and Dholavira in the south emerged as major urban centers. Several population centers also emerged along the Saraswati and Ghaggar-Hakra rivers (the Cholistan). This period marked the peak of the Harappan civilization with a strong trade network (Fig. 5c). Even though the Indus Tradition never realized itself as a centrally planned state, and the major urban centers had their own clans competing for power, the interdependencies between the urban centers and other centers was sufficiently strong to render Harappan Tradition a quasi-statehood (Kenoyer, 1994, 2006). The area settled was at its maximum in the history of the tradition, reflecting the growth in population and opulence resulting from gains in efficiency through specialization and trade (Vahia and Yadav, 2011; Madella and Fuller, 2006).

The span of influence, through trade and other interaction networks, that rendered Harappa its identity as a state, collapsed back into settlement areas to the west, south and east around 3900 BP, with little or no interaction between them (Kenoyer, 2011, 1995); see also Fig. 5d. Many Indus Valley settlements were abandoned during the transition from Mature Harappan to Late Harappan Phase, around the second millennium BC (Shaffer and Lichtenstein, 1995; Franke-Vogt, 2003). Kenoyer (1995) suggests that specialized crafts practiced during the Mature Harappan Phase differed from the practice of the localization era of the Indus Valley Tradition. The use of marine shells and grey-brown cherts was widespread in the cultural boundaries during the Mature Harappan Phase. The use of shell bangles have, however, rarely been reported between northern Punjab and Uttar Pradesh during the Late Harappan period, suggesting weak interaction networks. In Gujarat, the transition from the Mature Harappan to Late Harappan Phase witnessed a drop of grey-brown chert usage and a replacement by local silicates (Kenoyer, 1995). The use of Harappan writing and inscribed seals also declined, further indicating a weakening of the extended exchange network of the Mature Harappan Phase. Changes in bead technology in the Late Harappan period also indicated a breakdown of long-distance exchange in the Indus Valley. For example, the use of raw materials such as banded black appears to be new and to have come from areas further to the east (Kenoyer, 2005, 1995). However, there has also been much continuity in subsistence, specialized technologies and systems of weights, potentially rejecting the hypothesis of stark discontinuity, but rather indicating continuity of the Indus Tradition and networks at smaller scales (Kenoyer, 1991; Jarrige, 1995).

3.1 The debate

While many agree that climate change may have contributed to the demise of the Indus Civilization, strong disagreements between paleo-climatologists, cultural anthropologists and archeologists remain on the process of the demise. The uncertainty in the radiocarbon dating of archeological evidence is one cause for disagreement (MacDonald, 2011). The transition for the Harappan Tradition from its mature urbanized era to its late era of population dispersal was around a major climatic event. The paleo-discharge record based on the core data from the Arabian Peninsula off the coast of Gujarat indicates that the Indus discharge into the Indian Ocean dropped significantly around 4200 BP (Fig. 6). This event has been recorded in several other paleo records and has been blamed for the dispersal of other civilizations such as Mesopotamia (Staubwasser and Weiss, 2006; Bar-Matthews et al., 2003). However, it has also been argued that the Harappan Tradition matured from a collection of towns or settlements to a quasi-state with several urban centers in the face of increasing water stress, to the extent that it was flourishing even after the 4200 BP event (MacDonald, 2011; Madella and Fuller, 2006). The 4200 BP event at best triggered a change in the organization of human societies that took time to take effect.

The theory of endogenous change supports the latter argument. As many others have argued, the demise of the Indus Tradition was probably more complex than the result of an

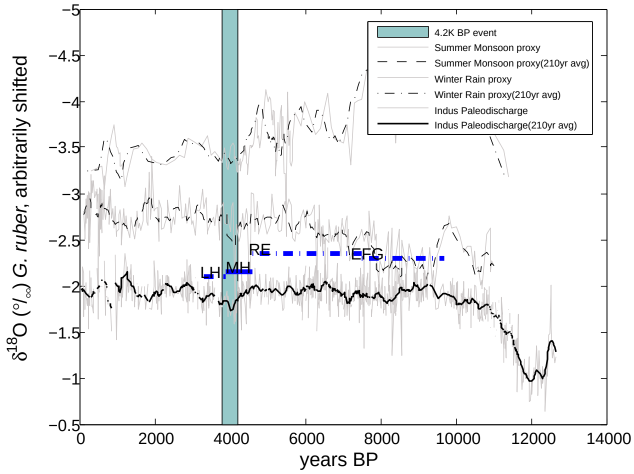

Fig. 6. The paleo-climatic proxies of the Indus River flow (Staubwasser et al., 2003), the summer rains (Stott, 2008) and the winter rains (Bar-Matthews et al., 2003) over the Holocene period. Lower negative value implies lower magnitude. Also indicated is the 4200 BP event. LH = Late Harappan Era, MH = Mature Harappan Era, RE = Regionalization era, EFG = Early Food Producing Era.

abrupt change in climate. Other variables such as resilience of human societies, prevalent institutions (that are proxies of cooperative structures) and technology matter as well (see for example the modeling results of Vahia and Yadav, 2011). Further, it is possible that the effect of climate change was not sudden and uniform throughout the basin. Since the spatial distribution of scarcity conditions engender cooperative structures, a cooperative state such as the Harappan civilization could have survived extreme scarcity conditions if the distribution was favorable.

Different water resource scarcity conditions at different locations facilitate specialization in the production of food and other commodities. This ensures that the scarce resource is used efficiently. Trade and interaction between different areas enables a distribution of products from such specialization based on local valuation of these products. In the Indus Basin, transition between the Early and Mature Harappan Era witnessed winter as well as summer crop production throughout the basin. As the Mature Harappan Era progressed, winter crops were grown more in the north and northwest regions, while the south and southeastern areas specialized more in summer crops (Madella and Fuller, 2006; Allchin, 1995a). Strong trade network and local scarcity conditions enabled the distribution of food throughout the year with sufficient surplus to support the roles of the administrators and the clergy. It resulted in the functioning of a quasi-state with institutions that reflected a cooperative structure at the basin scale. The scale of cooperation also facilitated technological innovation in water management and infrastructure, which ensured even more efficient use of water resources (Vahia and Yadav, 2011; Bisht, 2001).

However, as the theory of endogenous change suggests, the appearance of a cooperative structure due to trade or interaction depended on local valuations. Local specialization in producing winter or summer crops without any interaction between the population centers is a non-cooperative structure. Each region then had to support its population based on its own production. The cooperation between the regions appeared when the regions found it mutually beneficial to trade the products they specialized in. Any change that affected the nature of mutual benefits between regions affected the nature of cooperation.

We attempt to explain the rise and the demise of the Harappan Tradition in this context. Our qualitative analysis suggests that it was the interplay between the strengths of winter and summer rains that led to the Harappan rise and fall. Our theory of endogenous change follows closely the general preconditions for the rise of state-level society laid out by Kenoyer (1995, 1991). The production of surplus that is essential for the formation of state-level societies motivates the creation of social and economic interaction networks to bring together the diversity of major ecosystems and resource bases. Technological capacity to facilitate the ever-growing demand of a state-level society can be thought of as endogenous, in the sense that surpluses spur technological advancement through specialization of labor.

3.2 The rise and the dispersal of the Harappan Tradition: role of rainfall and the spatial distribution of scarcity conditions

The winter rains in the Indian subcontinent originate near the eastern Mediterranean (Staubwasser et al., 2003; Staubwasser and Weiss, 2006). The paleo-rainfall record from Soreq Cave in Isreal (Bar-Matthews et al., 2003) suggests that the strength of winter rains in the Indian subcontinent weakened over the Holocene. Meanwhile, the paleo-SST (sea surface temperature) record of the western tropical pacific (Stott, 2008) suggests first an increasing trend, followed by a decreasing trend around the beginning of Early Harappan Phase (Fig. 6). Both the paleo-records, given their correlation with winter and summer rains (McDonald, 2011), suggest that the rains stabilized to the current climatic condition in the late Holocene period around the collapse of the Harappan Tradition.

The Early Harappan Phase witnessed an increase in the winter rains strength (Fig. 7). It peaked and started to decline around the period when the Harappan Tradition entered its mature phase. Meanwhile, the summer rains' strength was declining throughout the Early to Late Harappan Phase (Thamban et al., 2007). Thus, the Harappan Tradition urbanized in the face of declining summer- and winter rain strengths. This was also recorded by the Indus paleodischarge data (Figs. 6 and 7). However, the detail of the mechanism of institutional change from urbanization to decline is not so evident in the paleo-discharge record. It is

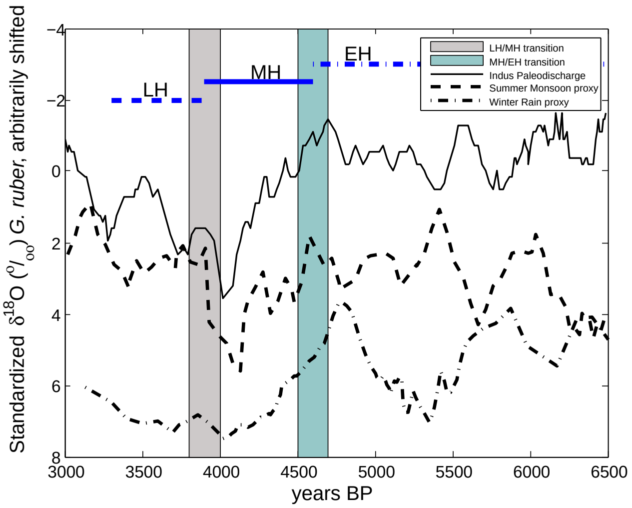

Fig. 7. The paleo-discharge and rains record during the rise and the dispersal of the Indus Tradition. The data are standardized by subtracting the mean and dividing by the standard deviation of the time series. Also shown are the transitions between EFG (early food producing) and EH; EH and MH and MH and LH. Compiled from Staubwasser et al. (2003), Stott (2008), Bar-Matthews et al. (2003) and Kenoyer (2006). LH = Late Harappan Era, MH = Mature Harappan Era, EH = Early Harappan Era.

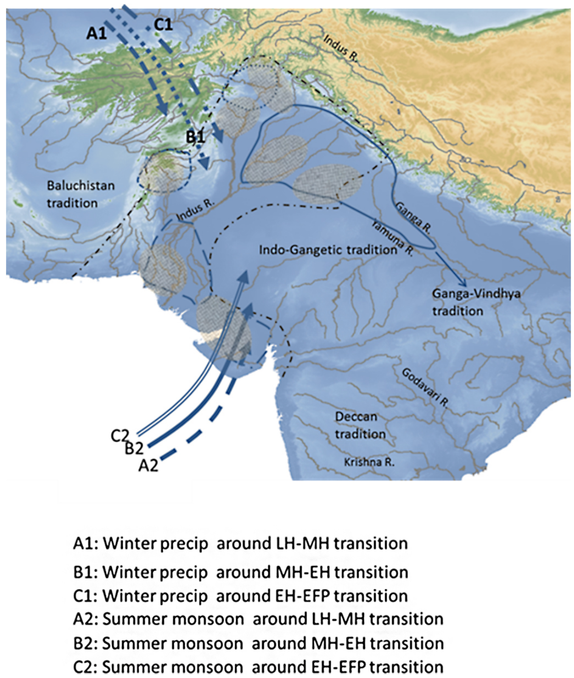

Fig. 8. The role of the strengths of the rains on the rise and the dispersal of the Indus Tradition. The lengths of the arrows indicate the magnitude of the rains. The directions of the arrows coarsely describe the flow of moisture. The hatched areas represent Early Harappan settlements and the smaller enclosed shapes are the extents of Late Harappan settlements. The extent of the Mature Harappan Era is represented by the dashed line.

instead evident in the changing strengths of the rains and hence the spatial distribution of water-scarcity conditions. Note that during the transition between the Early and Mature Harappan Phase, the Indus Valley also witnessed increasing population pressure that added to the social dimension of scarcity.

The winter season crop production in the Harappan Tradition coincided with the increasing strength of the winter rains towards the end of the Early Harappan Tradition (Fig. 7). The population (in terms of the number and area of settlements) also grew, sustained by the relative abundance of water and fertile land (Fig. 9). This implied local abundance of food, which ensured a carrying capacity that was sufficient to meet local demands. Given the relative abundance of rain and low, population density (Fig. 9), the need to trade for subsistence was low although various population centers were interacting (Kenoyer, 2001).

The weakening of winter rains during the mature phase and the ever-decreasing strength of the summer rains might have created the avenue for cooperation (Fig. 7). This is also corroborated by Fig. 7, which shows that the Harappan Tradition was in its mature era while the strengths of summer and winter rains (proxies) declined. Weakening winter rains meant that the rains penetrated the Indus Valley to a lesser extent. The eastern parts of the Indus Tradition shifted to summer crops; meanwhile, the north and the northeastern parts retained their specialization in winter crops (Madella and Fuller, 2006). Weakening summer and winter rains for the eastern and southern parts meant scarcer water conditions relative to the north and northwestern parts that still received water from the Indus River and its tributaries in relative abundance. Our theory supports the argument that a gradient of increasing water-scarcity conditions in the downstream direction under overall increasing scarcity conditions can favor upstream–downstream cooperative structures at the basin scale. Hence it supports the argument that Harappan Tradition rose to maturity even under decreasing water availability conditions.

This might have led to strong trade links throughout the basin and cultural uniformity, even though there was never a centrally planned Harappan Tradition that prevailed during the mature era of Harappan Tradition (Kenoyer, 2006). The non-zero sum nature of cooperation implied that both the upstream and downstream areas of the basin gained from the cooperative structure. This meant that there was surplus enough for elite classes to emerge and overall population to blossom (Fig. 9). The major urban centers such as Harappa and Mohanjo-daro saw powerful families competing to rule (Kenoyer, 2011). The society was more stratified.

However, the gains from mutual cooperation and trade might soon have thinned out due to further weakening of the summer and the winter rains (Figs. 7, 8). This also corroborates Kenoyer (1995), who suggested that its effects could

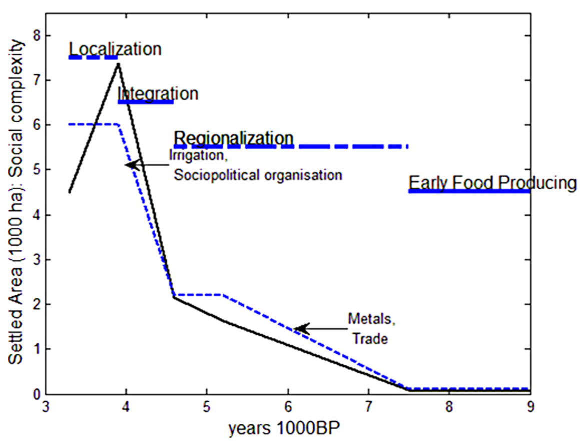

Fig. 9. The evolution of population density in terms of settlement area (after Madella and Fuller, 2006). Also shown are the various eras: Localization refers to Late Harappan Era, Integration refers to the Mature Harappan, Regionalization refers to the transition from the early Food Producing Era to the Early Harappan Era. The dashed line represents the carrying capacity of the basin, adapted from the modeling results of Vahia and Yadav (2011), which also shows that the transitions between the shown era was also complemented by technological innovations.

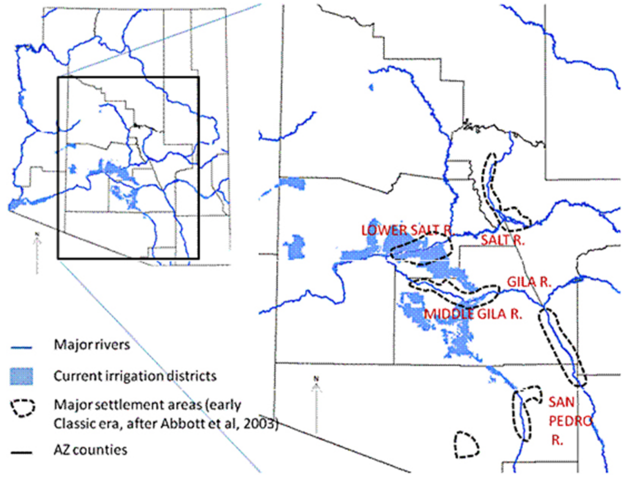

Fig. 10. Overview of Hohokam settlements in the Salt and Gila River areas (Early Classic area). Data source: Arizona State Land Department, Arizona Land Resources Information System, Major Rivers & County; Arizona Department of Water Resources, Irrigation districts; 11 July 2013 in Arizona Geospatial Data and Maps http://uair.arizona.edu/item/292543.

be devastating (for the regional agriculture) if both the summer and winter rains started to fail at the same time. While the tradition efficiently used water resources through innovative irrigation and other water resources management technologies, it needed newer technological innovation to cope with ever-increasing water stress (Bisht, 2001; Vahia and Yadav, 2011). The sudden population growth throughout the mature phase meant increased stress on the food production system (Madella and Fuller, 2006) and required improved food production technologies. Several of these much-needed technologies, such as the use of horses, appeared late (Kenoyer, 1995; Vahia and Yadav, 2011). Around the transition from mature to Late Harappan Era, the Ghaggar-Hakra and Saraswati rivers had dried out, possibly due to non-climatic causes. This meant further population stress on other settlements on the Indus River and other perennial rivers. The weakened winter rains further resulted in reduced seasonal snow in the headwaters of the Indus River system, which strained the water supply of an already stressed system (Staubwasser et al., 2003).

In light of the theory of endogenous change, changing rains strengths and increasing population pressure could have resulted in an unfavorable spatial distribution of water stress conditions that led to the collapse of the cooperative structure at the basin scale. This demise is the Late Harappan Era, when the scale of the cooperative structure collapsed from the basin scale to smaller autarkic units or isolated settlement areas (Figs. 8, 9). The weak or absent trade links between the Late Harappan settlements (Kenoyer, 2005, 1995) indicate that it was no longer beneficial to cooperate and that those societies were better off at local scale by sustaining their population through local production (Madella and Fuller, 2006), either by (1) settling in fertile areas as documented in the post-urban sites of eastern Punjab, northern Rajasthan and Haryana or (2) by intense cultivation of summer crops such as sorghum as documented in the post-urban sites of Saurashtra (Allchin, 1995a). This also meant localization of Harappan identity (Kenoyer, 1991; Jarrige, 1995; Allchin, 1995a). Locally, high-stress conditions also implied that populations out-migrated from the basin to less stressed areas of the Indo-Gangetic plains (Fig. 8). Thus the decline of the Indus Tradition coincided with the emergence of other traditions in the subcontinent such as the Ganga-Vindhya traditions and the Deccan Tradition (Kenoyer, 2006).

4 Hohokam civilization

The Hohokam is an archaeological culture found along the middle Gila and lower Salt rivers in the Phoenix Basin in the Sonoran Desert (see Fig. 10). The Hohokam occupied this area roughly between AD 1 and the middle of the 15th century AD. The Hohokam culture may be renowned for two things: their extensive irrigation canals, which were found by European settlers, and the apparent disappearance of the complete Hohokam society after roughly 1450. As such, the Hohokam is a popular symbol for the risks that societies run when they rely on a single source of food production and when they overstress that system.

Irrigated agriculture was important for the Hohokam, but they also relied rather heavily on harvesting wild plants, and

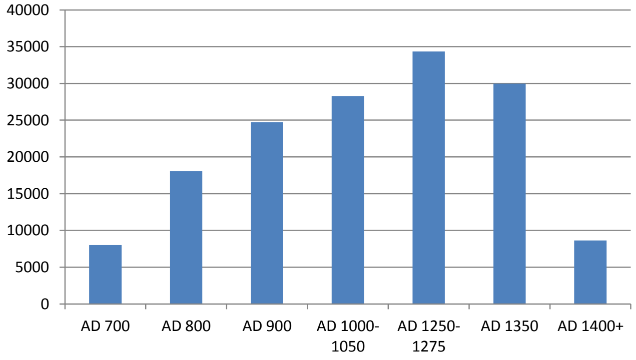

Fig. 11. Estimated total population for the Hohokam civilization, as reconstructed by the Long Term Vulnerability and Transformation project (http://core.tdar.org/dataset/1582).

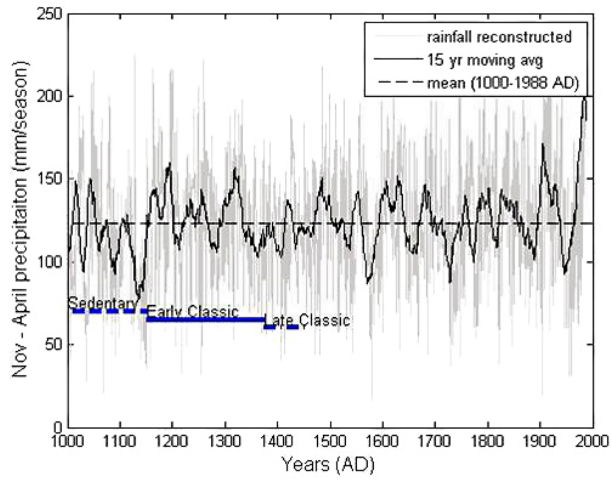

Fig. 12. Tree-ring reconstruction of winter precipitation (mm/season) in southwestern Arizona, United States from AD 1000 to 2000. Also shown are the three major eras of the Hohokam civilization and the mean of the time series over the entire period. Compiled from http://www.ncdc.noaa.gov/paleo/pubs/ni2002/az6.html; see also Ni et al. (2002).

they hunted animals as well. The principal field crops were maize, beans, cucurbits, and cotton. Agave was an important wild plant, used for both fibre and food, but it seems to have been grown within irrigated systems along canal banks. Mesquite was also a very important wild plant, both for food and wood (Gasser and Kwiatkowski, 1991; Hodgson, 2001; Rea, 1997). Wild mammals that were hunted and/or used include rabbits and hares, small rodents, white-tail and mule deer, pronghorn antelope and mountain sheep, as well as birds and fish (Fontana, 1983; Rea, 1997).

The Hohokam period is generally divided into four periods: the Pioneer (AD 450–750), Colonial (AD 750–950), Sedentary (AD 950–1150) and Classic (1150–1450) period (Woodson, 2010). Abbott et al. (2003) define the Classic period between AD 1100 and 1375, after which the so-called Polvoron Phase (AD 1375–1450) is found. During the Pioneer to Sedentary period the Hohokam culture was spatially the most extended of all the phases, with ball courts spread widely over huge areas. Hohokam ball courts are oval depressions of varying size – on average they measure some 30 by 15 m. Groups of people watched ball games; these meetings were also used to exchange goods and information, both within the Hohokam culture and between the Hohokam and other groups. As such, the number of ball courts is a good indicator of both the expansion of Hohokam groups and the general importance of economic and ceremonial activities.

In the Classic period major changes occurred. Many platform mounds are found in the area which date to the Classic periods, but the spatial pattern of these mounds was far less expansive compared to the distribution of the ball courts of the Sedentary period. The distribution of the mounds in the Classic period suggests a retreat of Hohokam society into more discrete clusters (Abbott et al., 2003). It is this change in the Classic period that is of clear interest to a study of the relations between human civilization and natural environment. In the Classic period, the Hohokam settlements in the Sonoran Desert are found in six clusters: the lower Salt and middle Gila River valleys of the Phoenix Basin, the Tonto Basin, the lower San Pedro River valley, the Tucson Basin, and the eastern Papaguería (Abbott et al., 2003, p. 5). Of these six areas, the lower Salt and Middle Gila areas were by far the largest in terms of population, dominating the overall population figures over time. Figure 11 shows these numbers. It is clear that the total population grew until the start of the Classic period, but started to decline in the second half of the Classic period. At the end of the Classic period, population estimates go down.

Originally, as the name suggests, the Classic period was seen as the core period of a flourishing Hohokam civilization. However, flourishing may be an optimistic way of describing the way Hohokam society managed to deal with the environment. The Hohokam did develop monumental architecture and extensive hydraulic infrastructure, but life must have been harsh along the Salt and Gila rivers. In a study of the Salt River, Abbott et al. (2003) find evidence of overpopulation, environmental degradation, resource stress, and poor health. Social fragmentation might have been the result. In short, in the Hohokam we find a civilization that experienced profound changes in its history, changes which were closely linked to the exploitation of their environment and the changes in that same environment. A main element of the environment was water availability. As will be discussed below, there is evidence suggesting that changes in management of the vital irrigation systems occurred especially in Pueblo Grande (located in the western part of the lower Salt area indicated in Fig. 10) and its associated irrigated system of the Salt River.

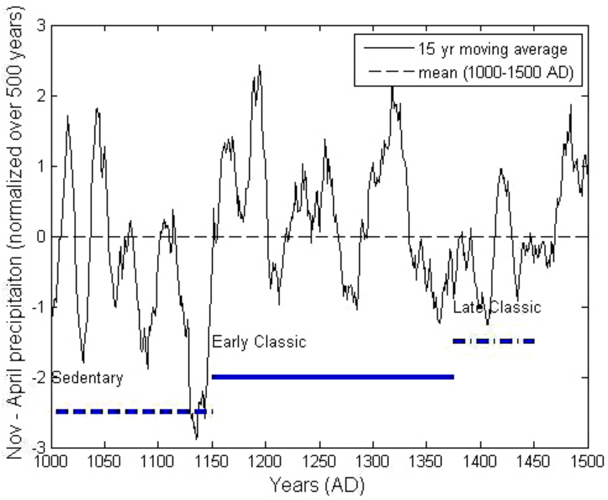

Fig. 13. The reconstructed and standardized (i.e., subtracting the mean and dividing by the standard deviation of the time series) winter precipitation (southwestern AZ, US) over the period of AD 1000–1500. The sharp drop of 3 standard deviations in winter season precipitation is evident around the transition of sedentary to early classic Hohokam. Compiled from http://www.ncdc.noaa.gov/paleo/pubs/ni2002/az6.html, see also Ni et al. (2002).

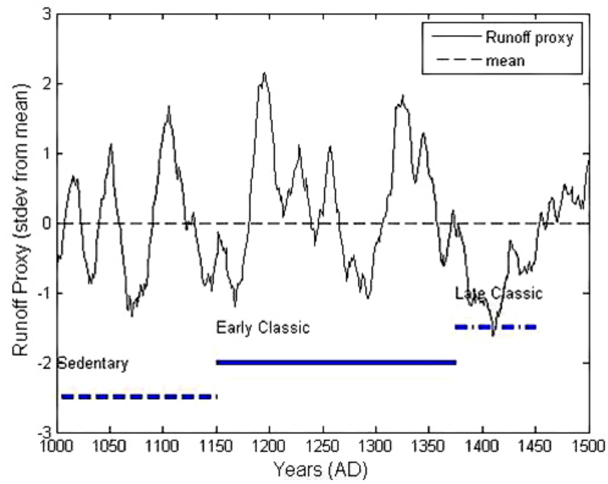

Fig. 14. A proxy for runoff conditions in the Hohokam. Obtained by subtracting reconstructed and standardized annual mean-maximum temperature from the reconstructed and standardized October through July precipitation for the southern Colorado Plateau. The standardization is for the period between AD 1000 to 1500. Compiled from Salzer and Kipfmueller (2005).

4.1 Changes and water in the Hohokam areas

The reconstructed data series on precipitation in the Phoenix area are available from from the "Tree-ring Reconstructions of Past Climate in the Southwest" project (http://www.climas.arizona.edu/projects/tree-ring-reconstructions-past-climate-southwest; last access: 21 March 2013). The data is available from AD 1000, which covers our time period of interest and provides us with the cool season (November–April) precipitation reconstruction. The reconstruction shows that only a few years in the past 1 000 years were drier than for example 2002. On average, the winter precipitation has not changed significantly in the last 1000 years. However, several extended dry periods can be found, and particularly for our time period in the late 1000s–early 1100s, and the late 1200s–early 1300s. However, sudden changes from dry to wet – increasing flooding along the rivers – may have been of importance as well. These sudden reversals from dry to wet were not uncommon in Hohokam times (Ni et al., 2002).

Redrafted graphs from this data set are provided in Figs. 12 and 13. We have also used reconstructed rainfall and temperature data for the southern Colorado plateau (Salzer and Kipfmueller, 2005; see Figs. 14 and 15). We are aware that other reconstructions of hydrological conditions in the Hohokam area are available as well (for example at http://treeflow.info/). The results of these data sets are typically not contradictory at all with the ones we used, but the temporal coverage of many data sets is not appropriate for our study.

The two drought periods, in the late 1000s–early 1100s, and the late 1200s–early 1300s, are of interest to our analysis. The first one coincides with a shift from the Sedentary to Early Classic period (Fig. 13). In this shift, abandonment of large tracts outside the major river valleys and a concentration of settlements closer to the riverine habitats occurred. This suggests less regional integration, and a stronger focus on individual settlements along the river. What exactly caused this shift in settlement is still heavily debated in Hohokam expert circles, but it is clear that environmental instability – like changes from winter- to summer-dominant rainfall patterns, decreasing moisture and increased stress on marginal agricultural land and irrigation alike – is one of the major candidates (Abbott et al., 2003). Warfare is also a candidate, but its causal relationship with environment and demography is unclear. Increased environmental stress could lead to warfare and population concentration in response to protection.

The environment in the Pueblo Grande area may have offered fewer possibilities in terms of plant and animal availability, and as a result human health would have deteriorated (Kwiatkowski, 2003; James, 2003; Sheridan, 2003). As a response to changes at the end of the Classic period, the Hohokam in the Salt River area seem to have re-organized themselves in sub-regional areas based on their irrigated areas. New social relations emerged between these areas, as the areas became more closed entities within the larger region. The late Classic period saw developments suggesting that those closed communities did relate to other groups; Abbott (2003) suggests that communities in the so-called Canal System 2 – the core area of Pueblo Grande – built relations with

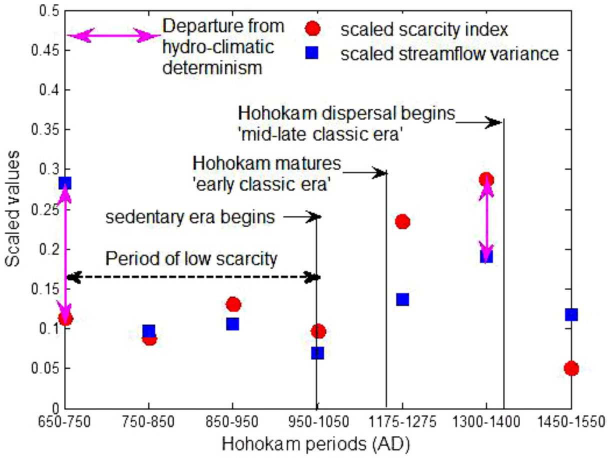

Fig. 15. Changes of "apparent" stochasticity of runoff availability over various periods in the Hohokam area. The stream flow variance and the scarcity index ("apparent" stochasticity) are scaled between 0 and 1 by dividing the values by its sum over the considered periods.

communities in Canal Area 1 – upstream of Pueblo Grande. Apparently, when these ties were built, the eastern part of the valley (upstream) became less populated and more isolated. All these developments together may show a tendency towards a centrally controlled, hydraulic network, which could be associated with a more central state-like institution (Abbott, 2003). Despite this development towards unity, at the end of the Classic period, a new period of drought and floods caused too much stress for the communities along the Salt River for it to survive.

Figure 14 is created from reconstructed annual (October to July) rainfall and temperature data for the southern Colorado Plateau (Salzer and Kipfmueller, 2005). We assumed that annual evapotranspiration is a linear function of annual mean-maximum temperature (Blaney–Criddle-type method). A runoff proxy is then defined as a linear function of the difference between annual rainfall and annual evapotranspiration. Since a standardization (by subtracting the mean and dividing by the standard deviation) of a linear function of a variable is the same as the standardization of the variable itself, we obtain a standardized runoff proxy as the difference between standardized annual rainfall and standardized annual-mean temperature. We then report the values of the proxy after applying a 15-year moving average filter. If the annual runoff proxy is assumed to be normally distributed, a standardized runoff proxy value of -1.5 is a relatively rare negative deviation with a probability of non-exceedance of around 7 %. This can be contrasted with conditions around AD 1175 when runoff had approximate probability of non-exceedance of around 15 %.

The period between AD 1275 and 1349 had the highest incidence of both droughts and floods, compared to the period AD 1000 and 1275 (Kwiatkowski, 2003; see also Fig. 15). Despite the clear signs of environmental change related to water and possible associated changes in Pueblo Grande, one needs to be careful in generalizing these findings for the entire Hohokam area – or vice versa. Some evidence from the Gila River, the other major area of Hohokam settlement, may be applicable to all riverine settlements of the Hohokam. For the settlement of Grewe in the Gila region, Ingram and Craig (2010) found that population figures decreased in above-average wet conditions, which suggests that a period of floods would put high stress levels on Hohokam society. Especially a community dependent on irrigation would need to repair the heads of the canal systems after each flood event, which might have demanded more labor than available or willing. For dry periods, Ingram and Craig did not find negative influence on population growth, which may be related to the (upstream) position of Grewe or the period of analysis (relatively early). They did find negative effects of combined wet and dry years.

However, when discussing irrigation management in the Gila and the possible changes over time, Woodson (2010) did not find big changes between the Sedentary and Classic periods in terms of irrigation organization. The Classic period did show lower population figures in the middle Gila River as well as a different population distribution within the area. Larger settlements were partly abandoned and smaller settlements were formed. Woodson did find changes in the irrigation systems along the Gila River that may be related to changing environmental conditions and/or stress on the resources. During the Sedentary period, two irrigation systems – the Gila Butte Canal and the Snaketown Canal – were connected, perhaps to convey excess water from Gila Butte into Snaketown Canal. The Classic period shows another connection between the two canals, which might have been built to transport the prevailing lower flows in the Gila River to the downstream end of the system. However, irrigation management did not seem to have changed: village systems generally were managed as a municipality, with political and irrigation authority being the same (Woodson, 2010).

4.2 Interpreting Hohokam change in relation to water availability and population growth

A cursory look at the regional hydro-climatic variations before AD 1000 may suggest that hydro-climatology was equally variable before the sedentary period, acclimatizing the society to such stochasticity. However, a more detailed analysis supports (a causal regularity predicted by) the theory of endogenous change proposed in this paper, just as in the case of Indus River basin. To illustrate this, we estimated the standard deviations of the runoff proxy for 100-year periods (650–750, 750–850, 850–950, 950–1050, 1175–1275, 1300–1400, 1450–1550), as these are the periods for which population figures are available (Fig. 11). Then, a measure of "apparent" scarcity is obtained as a product of runoff variance and population size (see the Appendix for the validity of such a measure). The scarcity measure, called "premium" in the Appendix, is an expression of the energy a population center may be willing to employ in order to avoid the stochasticity in the runoff proxy. We also term this premium as "apparent" stochasticity, since an increase in population has the effect of amplifying the variance of resource availability for a population center.

Figure 15 illustrates "apparent" stochasticity of runoff availability over the various periods we considered. The apparent increase in the stochasticity of scarcity may have motivated Hohokam population centers to initially cooperate and technologically innovate. Figure 15 suggests that the Hohokam area had relatively low ("apparent") scarcity and low runoff variance between AD 750–1000. There seems to have been a strong correlation between the variance of runoff proxy and the scarcity index. This relatively calm period of hydro-climatic determinism might have led to a transition from food gathering to sedentary life. As in the case of Indus, we find the Hohokam civilization maturing to a quasi-statehood during the times of increasing scarcity around AD 1150 (the beginning of the Early Classic era). During this period, we also witness the departure of the scarcity index from the hydroclimatic index. This provides evidence of the departure of the evolution of Hohokam society from hydro-climatic determinism. However, the energy needed to avoid "apparent" stochasticity might still have been relatively low. This might have resulted in a cooperative structure that scaled the entire study area. The Hohokam witnessed a dispersal of the larger cooperative networks around the peak of the scarcity index. The energy needed to avoid the "apparent" stochasticity might have been larger than the gains from cooperation. This might have led to the dispersal of population centers as they sought better areas to populate.

5 Synthesis: a comparative assessment

Our two different civilizations have both dealt with water scarcity, but there are important differences to be stressed between them. A first main difference is the temporal scale: the Indus tradition covered three millennia, whereas the Hohokam civilization lasted about one millennium and was studied for "only" five centuries. One may argue that such diverse scales may in part be due to the stochasticity in water resource availability. Water resource availability of the Indus Civilization was driven by winter and summer rains that gradually declined in strength. The Indus Civilization seems to have witnessed a gradual decline in water resource availability (over 500 years) in comparison to the Hohokam civilization, even though it is abrupt on an archeological scale – although this may be partially a result of data availability. As Fig. 14 demonstrates, Hohokam society faced immense fluctuations in annual water resource availability. The runoff proxy suggests that it fluctuated between $+2$ standard deviations (wet to dry) and -1.5 standard deviations (extremely dry) over a period of 500 years. Such "short" timescale fluctuations would have interrupted the way institutions were established and maintained by Hohokam society. This degree of stochasticity in annual water resource availability represents uncertainty that adds to the cost of building a coalition under water-scarce conditions (Pande and McKee, 2007).

Even though the two civilizations differed in spatiotemporal scales and evolution, both civilizations reached their peaks under increasing scarcity conditions and declined under extreme scarcity. The Indus Valley Civilization urbanized and integrated its various settlements spanning the western part of the Indian subcontinent under increased scarcity conditions (Figs. 5 and 7). The beginning of this decline in water resource availability was possibly due to the beginning of weakening winter rains. The summer rains had already weakened for the past millennium. The civilization began its decline after the local minima of winter and summer rains coincided. The rise of the Hohokam civilization to maturity (from the Sedentary to Classic era) occurred during the period of extremely low annual precipitation around AD 1150 (Figs. 12 and 13). The available water was relatively low but not extremely so (Fig. 14). Hohokam society started to disperse around AD 1375, under extremely low runoff conditions, even though annual precipitation had not been extremely low.

While the spatial distribution of scarcity is evident in the case of the Indus Civilization, it is not so clear for the Hohokam civilization. However, it witnessed the condition of increasing scarcity that we argue would be necessary (if not sufficient) for the emergence of basin-scale cooperation. The emergence of basin-scale institutions led to more effective consumption of resources. It brought prosperity and consequently population growth with it. The changes in population and water resources availability would have led to increasing stress on the available resources up to the extent that it had destabilizing effects on the cooperative structure in both civilizations. That led to societal decline, precipitated after extremely old water resource availability. It can be argued that both civilizations declined due to the efficiency in consumption of resources brought about by basin-scale cooperation. First, efficient consumption led to a quick increase in local population densities. Under no or slow technological innovations, an increasing population would have implied increasing demand for resources at a carrying capacity that did not increase over time. We argue that the stress conditions were further exacerbated when the carrying capacity of the system was unfavorably perturbed. That was the case in both the civilizations, though the mechanism through which it precipitated differed.

The Hohokam faced severe volatility in water resource availability (Figs. 14, 15). This implied fluctuations in its carrying capacity and amounted to severe uncertainty about the availability of future water resources. Such uncertainty, once realized by the cooperating agents in the cooperative structure of the Hohokam in the Classic era, was a cost.

Uncertainty in resource availability often distorts the solution of an allocation game (Pande and McKee, 2007). There is also evidence that populations migrated out of the cooperative structure during relatively wet periods only to come back later due to recurring dry conditions (Ingram and Craig, 2010). This could have added further strain on the personal relationships and exacted another cost of personal nature on the coalition structure, weakening it over time. The extremely low runoff period around AD 1400 could have been a threshold that led to the collapse of the Hohokam cooperative structure. On its turn, the Indus Civilization faced a gradual decline in rain strength. The carrying capacity of the basin gradually declined, while it faced ever-increasing demand due to increased population growth. The cooperative structure appeared to have been resilient at first to the deficit between population demand and the carrying capacity (that probably appeared around 4200 BP), but the resilience could apparently not sustain the basin-scale cooperation for long. Scarcity became sufficiently severe for agents who could no longer afford being in the basin-scale cooperative structure.

We do, however, acknowledge several uncertainties and/or weaknesses in our study. For example, there have been no adequate and accurate studies that can reconstruct the impact of the summer monsoon or the winter rain pattern for the ancient Indus Valley as a whole. Most recent studies are at small regional scale. Furthermore, the Early Harappan, Harappan and Late Harappan agriculture was not necessarily directly dependent on rainfall; it also benefited indirectly from rainfall through snowmelt. Further, we acknowledge that we cannot quantitatively test our theory with archaeological data alone, particularly as these data are fragmentary and incomplete. We also acknowledge that physical systems (water scarcity) need to be influenced by human responses (institutional change) at similar timescales of human decisions if feedbacks from human responses to physical systems need to be considered in contexts of endogenous change. However, we would like to highlight that we did not explore the endogenous (influenced by institutional change) hydrological factors that influence societal change. Our focus in this paper was to explore the feedback of (assumed exogenous) hydroclimatic change on institutional change. We do claim that this paper provides evidence and motivates further analysis of hydrological feedbacks resulting from human responses.

6 Conclusions

The rise of a civilization to maturity implies an emergence of a cooperative structure (as trade, irrigation, state or culture) at its spatial scale. The onset of the cooperative structure at the basin scale under increasing – not yet extreme – scarcity conditions is a regularity predicted by the theory of endogenous change. In both our case studies, cooperative structures of different kinds seem to have appeared at the scale of the study area under increasing scarcity conditions. We did observe the existence (and clearly not a breakdown) of a cooperative structure at low values of the scarcity index in both case studies. Emergence of cooperative structures seems to not have taken place under decreasing scarcity conditions or at high levels of scarcity. In both our cases, cooperative structures appear to have collapsed under relatively extreme water-scarce conditions. Thus, we claim that we find evidence to support the regularities predicted by the theory of endogenous change in both cases.

This does not mean that the theory predicts the emergence of basin-scale cooperation under any scarcity condition for any society. This paper discussed that a cooperative structure appears when the spatial distribution of scarcity conditions is such that cooperation is beneficial for settlements involved. Cooperation may not be the best strategy for all either under a condition of abundant resources or of extreme scarcity. In the case of abundance there is sufficient local availability of resources that dilutes the need to cooperate, while under extreme scarcity many may find cooperation unaffordable. Thus, scarcity conditions that are not yet extreme would be a necessary – but not a sufficient – condition for a cooperative structure to emerge. The spatial distribution of scarcity conditions matters as well, since scarcity is a reflection of local valuations of a resource. It is only under a diversity of local valuations that different agents would be willing to cooperate. In the case of systems connected at least by hydrology (such as in the basins considered in this paper), scarcity that increases in the downstream direction is a condition for the emergence of basin-scale cooperation; but we are the first ones to admit the need and call for further research on this issue.

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Appendix A

Apparent stochasticity

Consider a population center in a cooperative arrangement with other population centers in a region. Let the total number of population centers in the region (representing total population) be N_t. Let the total amount of runoff generated by the region at time t be S_t. Let the total runoff in the region be random and be represented by $S_t = \overline{S} + x_t$. Here $\overline{S}$ represents mean total runoff that is constant for all time t and x_t is a 0-centered random variable with standard deviation σ_t. We let σ_t vary over time. We also assume that x_t is the sum of population-center-specific randomness $x_{i,t}$ that is independent but identically distributed with mean 0 and variance $\hat{\sigma}_t$. Thus $\sigma_t = N_t \hat{\sigma}_t$. Thus we consider a case where the average of total runoff supply in the region does not change, but its stochasticity (measured by σ_t) changes over time. This would be reminiscent of the Hohokam case.

Let us assume that all the population centers share the total supply S_t equally. Thus, each population center i gets a share $c_{i,t} = \frac{S_t}{N_t} = \frac{\overline{S}}{N_t} + x_{i,t}$. Here $\frac{\overline{S}}{N_t}$ represents the deterministic part of a center's share and $x_{i,t}$ represents the uncertainty. Now let us assume that population centers are risk averse and derive utility from their share of form $u\left(c_{i,t}\right) = \frac{(c_{i,t})^\rho}{\rho}$, where $0 < \rho < 1$ measures the degree of risk averseness. The utility function remains unchanged over time, hence no technological innovation is incorporated.

The premium $P(\frac{\overline{S}}{N_t})$ that a population center is willing to pay for a deterministic share $\frac{\overline{S}}{N_t}$ and avoid uncertainty due to $x_{i,t}$ can be approximately given by (Silberberg and Suen, 2001, p. 406, Eqs. 13–11)

$$P\left(\frac{\overline{S}}{N_t}\right) = -\frac{1}{2}\hat{\sigma}_t^2 \frac{u"\left(\frac{\overline{S}}{N_t}\right)}{u'\left(\frac{\overline{S}}{N_t}\right)}.$$

Here $u"(c) = (\rho-1)c^{\rho-2}$ represents the second-order derivative and $u'(c) = c^{\rho-1}$ represents the first-order derivative. Thus $u"(c)/u'(c) = (\rho-1)c^{-1}$. For the given specification of the utility function and assuming that all the population centers have the same level of risk averseness, it can be shown that

$$P\left(\frac{\overline{S}}{N_t}\right) \propto \hat{\sigma}_t^2 N_t. \tag{A1}$$

Thus the RHS of the above equation, when scaled between 0 and 1, measures the relative premium to avoid uncertainty in runoff locally available. The premium, and hence the willingness to pay, to avoid uncertainty increases both with total population and the variance of runoff. The higher the premium, the higher the perception of scarcity is. Hence the premium is a measure of "apparent" scarcity.

Note that a population center can only afford a premium (energy) that it is willing to pay (invest) for cooperation if it produces an (expected) income larger than the premium. If the premium is unaffordable, the population cannot cooperate (even if it wants to). This is equivalent to stating that a cooperative structure collapses if the "apparent" stochasticity becomes sufficiently large.

References

Abbott, D. (Ed): Centuries of decline during the Hohokam Classic period at Pueblo Grande, University of Arizona Press, Tucson, 2003.

Abbott, D., Dale Breternitz, C., and Robinson, C. K.: Challenging conventional conceptions edited by: Abbott, D., 3–23, 2003.

Allchin, F. R.: The end of Harappan urbanism and its legacy, in: The Archaeology of Early Historic South Asia: The Emergence of Cities and States, edited by: Allchin, F. R., 26–40, Cambridge, Cambridge University Press, 1995a.

Allchin, F. R.: Early cities and states beyond the Ganges Valley, in: The Archaeology of Early Historic South Asia, edited by: Allchin, F. R., 123–151, Cambridge, Cambridge University Press, 1995b.

Ambec, S. and Sprumont, Y.: Sharing a river, J. Econ. Theor., 107, 453–462, 2002.

Bar-Matthews, M., Ayalon, A., Gilmour, M., Matthews, A., and Hawkesworth, C. J.: Soreq and Peqiin Caves, Israel Speleothem Stable Isotope Data, IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2003-061, NOAA/NGDC Paleoclimatology Program, Boulder CO, USA, 2003.

Bisht, R. S.: The water structures and engineering of the Harappans at Dholavira (India), in: South Asian Archaeology 2001, edited by: Jarrige, C. and Lefevre, V., Vol. 1, Proceedings of the Sixteenth International Conference of teh European Association of South Asian Archaeologists, 2–6 July, 2001, 11–25, 2001.

Boissevain, J.: The place of non-groups in the social sciences, Man, 3, 542–556, 1968.

Costanza, R., Graumlich, L. J., and Steffen, W. (Eds.): Sustainability or collapse? An integrated history and future of people on earth, MIT Press, 2011.

Dopfer, K., Foster, J., and Potts, J.: "Micro-meso-macro", J. Evolut. Eco., 14, 263–279, 2004.

Erdosy, G.: City states of North India and Pakistan at the time of the Buddha, in: The Archaeology of Early Historic South Asia, edited by: Allchin, F. R., 99–122, Cambridge, Cambridge University Press, 1995.

Ertsen, M. W., Murphy, J. T., Purdue, L. E., and Zhu, T.: A journey of a thousand miles begins with one small step – human agency, hydrological processes and time in socio-hydrology, Hydrol. Earth Syst. Sci. Discuss., 10, 14265–14304, doi:10.5194/hessd-10-14265-2013, 2013.

Fisher, Ch. T., Hill, J. B., and Feinman, G. M. (Eds.): The archaeology of environmental change. Socionatural legacies of degradation and resilience, University of Arizona Press, 2009.

Fontana, B. L.: Pima and Papago: Introduction, in: Southwest, edited by: Ortiz, A., Vol. 10 of Handbook of North American Indians,Washington DC, Smithsonian Institution, 125–136, 1983.

Franke-Vogt, U.: Excavations at Sohr Damb/Nal: Results of the 2002 and 2004 seasons, in: South Asian Archaeology 2003, edited by: Franke-Vogt, U. and Weisshaar, H.-J., Proceedings of the Seventh International Conference of the European Association of South Asian Archaeologists, 7–11 July 2003, Bonn, 63–76, 2003.

Gasser, R. E. and Kwiatkowski, S. M.: Food for thought: recognizing patterns in Hohokam subsistence, in: 1991 Exploring the Hohokam: Prehistoric Desert Peoples of the American Southwest, edited by: Gumerman, G. J., Albuquerque NM, University of New Mexico Press, 417–459, 1991.

Greif, A. and Laitin, D. D.: A theory of institutional change, Am. Polit. Sci. Rev., 98, 633–652, 2004.

Hall, P. A.: Historical institutionalism in rationalist and sociological perspective, edited by: Mahoney, J. and Thelen, K., Explaining Institutional Change: Ambiguity, Agency, Power (New York, Cambridge University Press), 2009.

Hodgson, W.: Food Plants of the Sonoran Desert, Tucson, University of Arizona Press, 2001.

Ingram, S. E. and Craig, D. B.: Streamflow and population dynamics along the Middle Gila River, J. Arizona Archaeo., 1, 34–46, 2010.

James, S. R.: Hunting and fishing patterns leading to resource depletion, edited by: Abbott, D., 70–81, 2003.

Janssen, M. A. and Anderies, J. M.: Stylized models to analyze robustness of irrigation systems, edited by: Kohler, T. A. and Van der Leeuw, S. E., 157–173, 2007.

Jarrige, J.-F.: From Nausharo to Pirak: continuity and change in the Kachi/Bolan region from the 3rd to the 2nd millennium B.C., in: South Asian Archaeology 1995, edited by: Allchin, R. and Allchin, B., Proceedings of the 13th International Conference of the European Association of South Asian Archaeologists, Science Publishers Inc. USA and Oxford & IBH Publishing Co. Pvt. Ltd. New Delhi, 11–32, 1995.

Kenoyer, J. M.: The Indus Valley tradition of Pakistan and western India, J. World Prehist., 5, 331–385, 1991.

Kenoyer, M. J.: The Harappan State. Was it or Wasn't it? In From Sumer to Meluhha: Contributions to the Archaeology of South and West Asia in Memory of George F. Dales, Jr., edited by: Kenoyer, J. M., Wisconsin Archaeology Reports, Vol. 3, 71–80, Department of Anthropology, U.W. Madison, 1994.

Kenoyer, J. M.: Interation systems, specialized crafts and culture change: The Indus Valley tradition and the Indo-Gangetic tradition in South Asia, in: The Indo-Aryans of Ancient South Asia, edited by: Erdosy, G., 213–257, Berlin, Walter de Gruyter & Co, 1995.

Kenoyer, M. J.: Early Developments of Art, Symbol and Technology in the Indus Valley Tradition, INDO-KOKO-KENKYU, Indian Archaeological Studies, 22, 1–18, 2001.

Kenoyer, M. J.: Bead Technologies at Harappa, 3300–1900 BC: A comparative summary, in: South Asian Archaeology 2001, edited by: Jarrige, C. and Lefèvre, V., Paris, Editions Recherche sur les Civilisations -ADPF, 2005.

Kenoyer, M. J.: Cultures and Societies of the Indus Tradition, in: Historical Roots in the Making of "the Aryan", edited by: Thapar, R., 21–49, New Delhi, National Book Trust, 2006.

Kenoyer, M. J.: Changing Perspectives of the Indus Civilization: New Discoveries and Challenges, Puratattva, 41, 1–18, 2011.

Komakech, H. C., van der Zaag, P., and van Koppen, B.: The dynamics between water asymmetry, inequality and heterogeneity sustaining canal institutions in the Makanya catchment, Tanzania, Water Pol., 14, 800–820, 2012.

Kwiatkowski, S. M.: Evidence for subsistence problems, edited by: Abbott, D., 48–69, 2003.

Lansing, J. S.: Complex adaptive systems, Annu. Rev. Anthropol., 32, 183–204, 2003.

MacDonald, G.: Potential influence of the Pacific Ocean on the Indian summer monsoon and Harappan decline, Quaternary Int., 229, 140–148, 2011.

Madella, M. and Fuller, D. Q.: Palaeoecology and the Harappan civilisation of south Asia: a reconsideration, Quaternary Sci. Rev., 25, 1283–1301, 2006.

Mithen, S.: Thirst: Water and power in the ancient world, Weidenfeld and Nicolson, 2012.

Ni, F., Cavazos, T., Hughes, M. K., Comrie, A. C., and Funkhouser, G.: Cool-season precipitation in the southwestern USA since ad 1000: comparison of linear and nonlinear techniques for reconstruction, Int. J. Climatol., 22, 1645–1662, 2002.

Orlove, B. S.: Ecological Anthropology, Ann. Rev. Anthropol., 9, 235–273, 1980.

Ostrom, E. and Basurto, X.: Crafting analytical tools to study institutional change, J. Instit. Eco., 7, 317–343, 2011.

Pande, S.: Autarkic thresholds to cooperative basin scale water management, in preparation, 2013.

Pande, S. and McKee, M.: Valuing certainty in a consensus-based water allocation mechanism, Water Resour. Res., 43, W02427, doi:10.1029/2004WR003890, 2007.

Pande, S., van den Boom, B., Savenije, H. H. G., and Gosain, A. K.: Water valuation at basin scale with application to western India, Ecol. Econom., 70, 2416–2428, doi:10.1016/j.ecolecon.2011.07.025, 2011.

Pande, S., Ertsen, M., and Sivapalan, M.: Endogenous technological and population change under increasing water scarcity, Hydrol. Earth Syst. Sci. Discuss., 10, 13505–13537, doi:10.5194/hessd-10-13505-2013, 2013.

Rea, A.: At the River's Green Edge: An Ethnobotany of the Gila River Pima. University of Arizona Press, Tucson, 1997.

Romer, P.: Endogenous Technological Change, J. Pol. Econ., 98, No. 5, Part 2: The Problem of Development: AConference of the Institute for the Study of Free Enterprise Systems (October, 1990), S71–S102, 1990.

Salzer, M. W. and Kipfmueller, K. F.: Southern Colorado Plateau Temperature and Precipitation Reconstructions. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2005-066, NOAA/NCDC Paleoclimatology Program, Boulder CO, USA, 2005.

Scarborough, V. L.: The flow of power, Ancient water systems and landscape, SAR Press, 2003.

Shaffer, J. G. and Lichtenstein, D. A.: The concepts of "cultural tradition" and "palaeoethnicity" in South Asian archaeology, in: The Indo-Aryans of Ancient South Asia: Language, Material Culture and Ethnicity, edited by: Erdosy, G., Berlin, New York, de Gruyter & Co, 1995.

Sheridan, G. S.: Childhood health as an indicator of biological stress, edited by: Abbott, D., 82–106, 2003.

Silberberg, E. and Suen, W. C.: The structure of economics: a mathematical analysis, McGraw-Hill, 668 pp., 2001.

Sivapalan, M., Savenije, H. H. G., and Blöschl, G.: Socio-hydrology: A new science of people and water, Hydrol. Process., 26, 1270–1276, doi:10.1002/hyp.8426, 2012.

Staubwasser, M. and Weiss, H.: Holocene Climate and Cultural Evolution in Late Prehistoric-Early Historic West Asia, Quaternary Res., 66, 372–387, 2006.

Staubwasser, M., Sirocko, F., Grootes, P. M., and Segl, M.: Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability, Geophys. Res. Lett., 30, 1425, doi:10.1029/2002GL016822, 2003.

Steinmo, S.: What is historical institutionalism?, in: Approaches in the Social Sciences, edited by: Porta, D. D. and Keating, M., Cambridge UK, Cambridge University Press, 2008.

Stott, L.: Pacific Warm Pool MD98-2181 Late Pleistocene Foraminiferal SST Data. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2008-030, NOAA/NCDC Paleoclimatology Program, Boulder CO, USA, 2008.

Thamban, M., Kawahata, H., and Rao, V. P.: Indian summer monsoon variability during the holocene as recorded in sediments of the Arabian Sea: Timing and implications, J. Oceanogr., 63, 1009–1020, 2007.

Thelen, K.: Historical Institutionalism in comparative politics, Annu. Rev. Polit. Sci., 2, 369–404, 1999.

Vahia, M. N. and Yadav, N.: Reconstructing the History of Harappan Civilization, Social Evolut. Hist., 10, 27–49, 2011.

Vayda, A. P. and McCay, B. J.: New directions in Ecology and Ecological Anthropology, Annu. Rev. Anthropol., 4, 293–306, 1975.

Woodson, M. K.: The Social Organization of Hohokam Irrigation in the Middle Gila River Valley, Arizona, Arizona State University, 2010.