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# Adaptation to Variable Environments, Resilience to Climate Change

## Investigating *Land, Water and Settlement* in Indus Northwest India

by Cameron A. Petrie, Ravindra N. Singh, Jennifer Bates, Yama Dixit,  
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Vikas Pawar, David I. Redhouse, and Dheerendra P. Singh

This paper explores the nature and dynamics of adaptation and resilience in the face of a diverse and varied environmental and ecological context using the case study of South Asia's Indus Civilization (ca. 3000–1300 BC). Most early complex societies developed in regions where the climatic parameters faced by ancient subsistence farmers were varied but rain falls primarily in one season. In contrast, the Indus Civilization developed in a specific environmental context that spanned a very distinct environmental threshold, where winter and summer rainfall systems overlap. There is now evidence to show that this region was directly subject to climate change during the period when the Indus Civilization was at its height (ca. 2500–1900 BC). The Indus Civilization, therefore, provides a unique opportunity to understand how an ancient society coped with diverse and varied ecologies and change in the fundamental environmental parameters. This paper integrates research carried out as part of the *Land, Water and Settlement* project in northwest India between 2007 and 2014. Although coming from only one of the regions occupied by Indus populations, these data necessitate the reconsideration of several prevailing views about the Indus Civilization as a whole and invigorate discussion about human-environment interactions and their relationship to processes of cultural transformation.

### Adapting to Variable Environments, Being Resilient to Changing Climates

Given the considerable importance of climate, climate change, and human/environment relationships in the present, it is per-

haps no surprise that there is ongoing interest in the way that humans caused and/or responded to environmental and ecological change in the past (Barnes et al. 2013; Diamond 2005; Staubwasser and Weiss 2006). Unquestionably, there is much to learn from the past about the success or failure of adap-

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tations to particular environments and ecological niches and the sustainability and resilience of responses to environmental pressures and climatic threats. Disentangling these dynamics is not, however, a straightforward process, and it is increasingly recognized that responses to environmental change are neither deterministic nor straightforward; particularly because environmental parameters, human behavior, and the interrelationship between these two elements are inherently complex (McAnany and Yoffee 2009; Miller, Moore, and Ryan 2011). This line of thinking recognizes that humans and the environment are neither independent nor simple variables; rather, they are both complex and interlinked in what has been described as both panarchy and a social-ecological system (SES) that witnesses cycles of resilience and adaptive change (e.g., Berkes, Colding, and Folke 2003; Gunderson and Hollig 2002). Leslie and McCabe (2013:116) have noted that while the concepts of resilience and adaptive change have been explored conceptually, empirical analysis remains rare, at least partly because resilience is difficult to measure in the context of complex socioecological systems. Archaeologists can play a unique role here as they are able to empirically investigate the before, during, and after of past instances of success or failure, thus furthering understanding of adaptation, resilience, and human response to climate change (cf. Mitchell 2008; Van de Noort 2011).

Although archaeologists recognize that human behavior is nuanced and varied, much of the debate about the impact of climate change on ancient civilizations has tended to be simplistic, both in terms of empirical approach and conceptual grounding. Debate has been dominated by numerous attempts to correlate global-scale climate records and the timing of local-scale cultural transformations that are visible in the archaeological record (e.g., deMenocal 2001; Haug et al. 2003; Staubwasser et al. 2003; Staubwasser and Weiss 2006), despite recognition that there is rarely direct evidence to link the two data sets (e.g., Aimers and Hodell 2011). As a result, inferences tend to be speculative and end up in “correlation equals causation” circularity. Furthermore, despite attempts to the contrary, there remains a fundamental disconnect between scientific approaches to understand global climate and the dynamics of climate change, on the one hand, and humanistic approaches to understand how human populations perceive climate and respond to climate change on the other (Barnes et al. 2013). Part of the problem is that archaeologists often uncritically look to distant climate data sets to interpret local cultural dynamics, while paleoclimatologists tend to uncritically look for cultural correlates to the climatic events that they observe (Aimers and Hodell 2011).

Archaeologists are now increasingly interested in understanding the ways that humans respond to change and the degree to which their societies and choices are sustainable and facilitate resilience (e.g., McAnany and Yoffee 2009; Miller, Moore, and Ryan 2011). This does, however, present significant empirical challenges as there is growing consensus that in order to properly comprehend human adaptation, sustain-

ability, and resilience, it is essential to consider local climatic and environmental conditions (e.g., Aimers and Hodell 2011; Dixit, Hodell, and Petrie 2014; Madella and Fuller 2006). In fact, it is arguable that an understanding of the local context is essential for establishing whether past human societies were willing, able, or, in fact, required to respond to global-scale pressures and potential threats.

Focusing on the local context also allows for nuanced exploration of the relationships between adaptation and resilience. While resilience can be viewed in terms of response to distinct step changes in climatic systems, behavior may already be adapted to ecological regimes that are intrinsically variable during single years and between years, which may make them predisposed to resilience. This fits neatly with what N. Miller (2011) has described as “predictable unpredictability,” where populations make use of subsistence and cultural strategies that are tailored to absorb and mitigate risk.

This paper will explore the nature and dynamics of adaptation and resilience in the face of a diverse and varied environmental and ecological context using the case study of South Asia’s Indus Civilization (ca. 3000–1300 BC), and although it will consider the Indus region as a whole, it will focus primarily on the plains of northwest India. Most early complex societies developed in regions where the climatic parameters faced by ancient subsistence farmers were varied but rain falls predominantly in one season. The Indus Civilization stands apart from other early complex societies for a number of reasons, but the significance and ramifications of the specific environmental context within which it evolved is not widely recognized outside of Indus research circles. Importantly, the geographical spread of the Indus Civilization spanned a very distinct environmental threshold, where winter and summer rainfall systems overlap and steep rainfall gradients are also evident. It, therefore, provides a unique opportunity to understand how an ancient society coped with both diverse and varied ecologies as well as change in the fundamental and underlying environmental parameters.

### The Cultural and Environmental Context of the Indus Civilization

The Indus Civilization was one of the great early complex societies of the Old World, and during its urban phase (ca. 2600–1900 BC), it spanned large parts of modern Pakistan and India (Agrawal 2007; Chakrabarti 1999; Fairservis 1967, 1971; Kenoyer 1998; Lal 1997; Marshall 1931; Possehl 2002; Sankalia 1962; Wheeler 1968; Wright 2010). The Indus Civilization has, however, been marginalized or excluded in much of the comparative literature on early complex societies, which is unfortunate, as it has much to contribute. For example, it has been argued that the Indus Civilization does not neatly conform to the prevailing models for early complex societies; for instance, the major Indus architectural structures that have been exposed do not match expectations of monumentality (e.g., Possehl 1998; although see Yoffee 2005:228–229). While

there is a lack of consensus about Indus sociopolitical structure and organization (e.g., Kenoyer 1994; Possehl 1998; Wright 2010), this actually serves to emphasize that interpretation of socioeconomic structures can be challenging in the absence of texts that can be readily translated (e.g., Parpola 1994).

It is clear that following a protracted period of village-based settlement, the urban phase of the Indus Civilization developed on the plains of modern Pakistan and northwestern India (fig. 1A) during the mid-third millennium BC (~4.6–4.5 ky BP). It has been claimed that during this phase, Indus settlements were distributed across an area of ca. 1 million km<sup>2</sup> concentrated around the river systems of northwest South Asia (Agrawal 2007:3; Possehl 2003:1). While this is an overestimation of the actual area occupied by Indus populations, our present understanding of settlement distribution suggests that the Indus Civilization was likely the most geographically extensive of all the early Old World civilizations (cf. Agrawal 2007; Possehl 2003; Wheeler 1968:4).

Present knowledge indicates that there was a constellation of four or five particularly large Indus settlements, which are usually described as cities (Mohenjo-daro, Harappa, Rakhi-garhi, Dholavira, and possibly Ganweriwala; Kenoyer 2008: 188; Petrie 2013:91). The inhabitants of these cities produced, used, and traded distinctive types of material culture, including painted pottery and figurines that were presumably made locally, and jewelry, standardized weights, and stamp seals that were made from raw materials typically obtained from medium- and long-range sources (the abundance of relevant specialist reports are reviewed recently in Wright 2010:148–166, 182–203; also Coningham and Young 2015:211–223). In a landscape dominated by rural settlements, Indus cities appear to have been the exception rather than the norm (Petrie 2013). The substantial distances between the major centers (at least 280 km) have been used to suggest that they each controlled vast hinterlands (e.g., Kenoyer 1997:54, 1998:50, table 3.1). It is, however, also probable that large and medium-sized settlements played an important and, perhaps, independent rather than subordinate role in both interactive processes and socio-economic control structures (Petrie 2013:91, 94–95; Sinopoli 2015:322).

To some extent, the pattern of material evidence seen at the city-sites has also been observed at large, medium, and small settlements, and this has led to the suggestion that there was marked uniformity in some aspects of Indus material culture (e.g., seals, weights, script; Agrawal 2007:7; Chakrabarti 1999: 179ff.; Kenoyer 2008:207; H. M.-L. Miller 2013; Wright 2010: 23, 327, 334). While similarities between some cultural elements have been emphasized, variation in material and human behavior has been recognized for some time and is increasingly being acknowledged (e.g., Ajithprasad 2011; Joshi 1984; Meadow and Kenoyer 1997:139; Petrie 2013:91, 95; Possehl 1982, 1992, 2002; Weber, Barela, and Lehman 2010; Wright 2010:180ff.). This variation is particularly evident in subsistence practices (e.g., Vishnu-Mittre and Savithri 1982:215; Weber 1999; Weber, Barela, and Lehman 2010; Weber and

Kashyap 2016; Weber, Barela, and Lehman 2010), settlement systems (Petrie 2013), and the production and use of particular categories of material culture, most notably figurines and ceramic vessels (e.g., Parikh and Petrie, forthcoming; Petrie 2013; Uesugi 2011).

It has long been recognized that there is considerable variation in climate, hydrology, and ecology across the extensive area in which Indus settlements are found (e.g., Agrawal and Sood 1982; Joshi 1984; Possehl 1982, 1992; also Chakrabarti 1999:153–160; Shinde et al. 2006; Wright 2010:166–170), but the specifics of this diversity and the degree to which it maps onto cultural variation has not been addressed in detail. Environmental factors undoubtedly placed specific constraints on cultural behavior and the choices open to the inhabitants of the various Indus regions, and it is arguable that comprehending the ways in which humans interacted with diverse and potentially changing environments over time and across space is critical for understanding the rise, flourish, and decline of Indus urbanism (cf. Agrawal and Sood 1982; Petrie 2013).

The underappreciation of the degree and implications of cultural and environmental variation across the Indus zone is particularly telling when it comes to explaining the decline and ultimate abandonment of the Indus urban centers. This process appears to have been accompanied by a reduction in settlement density in the western and central parts of the Indus zone and an increase in the number of village-sized settlements in its eastern reaches (i.e., Haryana/Punjab and Gujarat; fig. 1B). Indus urban decline has been referred to as a collapse or a transformation, and from the beginnings of research on the Indus Civilization, both natural and human factors have been invoked as likely causes (e.g., Allchin 1995; Marshall 1931; Possehl 1997a, 1997b; Ramaswamy 1968; Wright 2010). There is, however, no consensus as to which factors are the most significant, and there have been substantial gaps in the evidence that might enable us to assess the process as a whole. These gaps include a shortage of focused research on the socioeconomy of the posturban and subsequent periods, a lack of absolute dates, and little high-resolution climatic and environmental evidence directly from the region.

Given these limitations in the evidence, it is perhaps unsurprising that there has been no agreement about the significance of climate and climate change on the Indus Civilization. Some have argued that there is no conclusive evidence to show that there is any difference in annual rainfall patterns between 6000 BP and the present (e.g., Kenoyer 1997, 2008: 186; Possehl 1997a), while others have posited climate change as the primary cause for the collapse and/or transformation of the Indus Civilization (e.g., Clift and Plumb 2008:205–210; Giosan et al. 2012; Shinde et al. 2006; Staubwasser and Weiss 2006). Within the diverse zone occupied by Indus populations, environmental factors related to hydrology were certainly important, and shifting/drying rivers and floods have long been proposed as major culprits. There have, for example, been extensive arguments made for and against the impact of flooding at Mohenjo-daro (e.g., for: Raikes 1965, 1968; Raikes



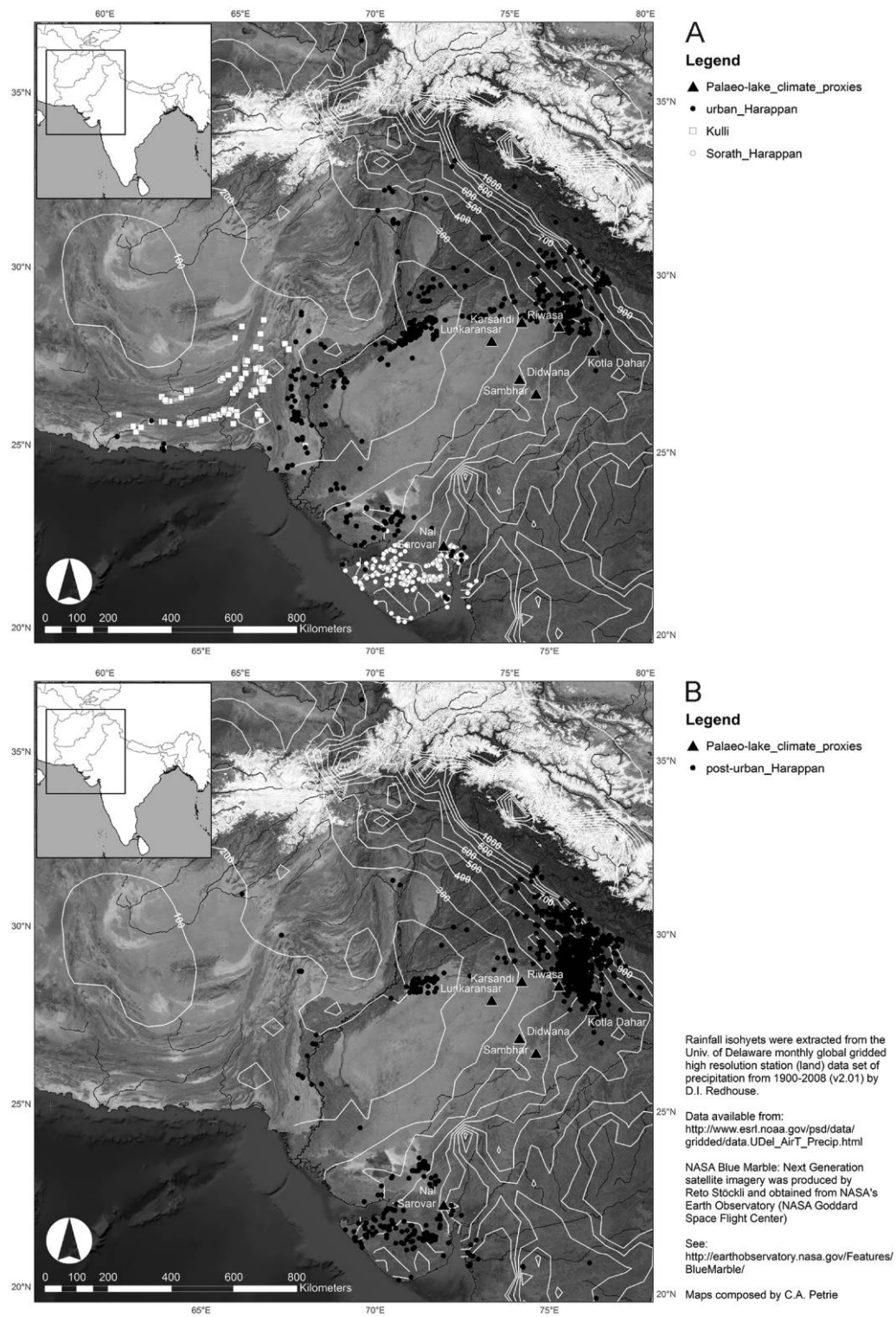


Figure 1. Distribution of urban-phase Indus settlements (including sites with Kulli and Sorath-Harappan material; A) and post-urban-phase Indus settlements (B) and their relationship to the distribution of mean annual rainfall recorded between 1900 and 2008. A color version of this figure is available online.

and Dales 1977; against: Lambrick 1964, 1967). We also now have detailed reconstructions of river shifts in Sindh, which demonstrate the movement of the main Indus channel between 4000 and 2000 BC (e.g., Flam 1981, 1993, 1999, 2013; Jorgensen et al. 1993). Furthermore, remote sensing has suggested that settlement patterns in southern Punjab may have responded to the dynamics of the Beas River system (Wright and Hritz 2013). These reconstructions and other geomorphological investigations also provide insight into the other major topic of hydrological discussion, the impact of the drying of the Ghaggar/Hakra River, which is often equated with the “lost” Saraswati River (e.g., Clift et al. 2012; Danino 2010; Ghose, Kar, and Husain 1979; Giosan et al. 2012; Lal 2002; Mughal 1997; C. F. Oldham 1874, 1893; R. D. Oldham 1886; Shinde et al. 2006; Stein 1942; Valdiya 2002; Wilhelmy 1969; Yash Pal et al. 1980; also Flam 1999, 2013). In northwest India, connections between climate change and river shift have been mooted (e.g., Giosan et al. 2012), and it has also been posited that neotectonic processes have been a factor in reshaping hydrology (e.g., Puri and Verma 1998).

A number of separate archaeological projects have applied multidisciplinary analysis of environmental parameters impacting Indus populations, incorporating geology, geomorphology, and bioarchaeology (e.g., Sindh Archaeological Project: Flam 1981, 1993, 1999, 2013; Jorgensen et al. 1993; Mission Archéologique Française en Inde: Courty 1985, 1995; Courty, Goldberg, and Macphail 1989; Francfort 1985; Gentelle 1985; Harappa Archaeological Research Project: Amundson and Pendall 1991; Belcher and Belcher 2000; Meadow 1991; Weber 2003; Beas Landscape and Settlement Survey: Schuldenrein, Wright, and Khan 2007; Wright 2010; Wright, Bryson, and Schuldenrein 2008; Wright and Hritz 2013; Wright, Khan, and Schuldenrein 2002, 2005a, 2005b; Indus Project of the Research Institute for Humanity and Nature: Rajaguru and Deo 2008; Shinde et al. 2008; Weber, Kashyap, and Mounce 2011). However, thus far, there have been only limited attempts to correlate and integrate the findings of these projects (e.g., Schuldenrein, Wright, and Khan 2007; Wright 2010: 25–44). There has also been only limited attention to proxy evidence for ancient climate that is proximate to the Indus zone and/or can be connected directly to the archaeological record.

Climate has long been considered an important parameter for understanding the Indus Civilization, starting from Marshall's (1931:2; after Stein 1931) suggestion that there has been a significant decrease in rainfall since the Indus period. In querying this interpretation, Raikes and Dales (1961) highlighted the “importance of integrating *all* types of evidence and checking on the inferences drawn from them” (279). However, traditionally, there has been an underappreciation of the relationships between the environmental and cultural dynamics that were in action. As elsewhere, archaeologists considering the Indus case have tended to either under- or overemphasize the possible role of climate (e.g., Clift and Plumb 2008:205–210; Giosan et al. 2012; Kenoyer 1997, 2008:186; Possehl 1997a; Shinde et al. 2006; Staubwasser and Weiss 2006). Fur-

thermore, when climate has been invoked as a critical driver of social change, there has been a reliance on distant climate proxy data sets for support (e.g., Giosan et al. 2012; Staubwasser and Weiss 2006), which is at least partly because of the lack of proximate proxy data that might inform us about its impact on the diverse local context. A range of climate proxy data is certainly available from various locations in the subcontinent, particularly from dry lakes in Rajasthan (e.g., Enzel et al. 1999; Prasad and Enzel 2006), and new proxy data sets continue to become available (e.g., Leipe et al. 2014; Prasad et al. 2014; Sarkar et al. 2015), but they are typically not proximate to the Indus zone. Unfortunately, the highest-resolution proxy data currently available comes from regions far outside the Indus zone that are characterized by different weather systems (e.g., Oman: Fleitmann et al. 2003; northeast India: Berkelhammer et al. 2012), while the more proximate data sets are either lacking in chronological precision or do not actually cover the critical period of the late-third and early second millennium BC (see Madella and Fuller 2006:1287ff., figs. 2, 9; Possehl 1999:259–263, fig. 3.112). Until recently, the most direct insights from within the Indus zone have come from modeling of the Intertropical Convergence in central Punjab (Wright, Bryson, and Schuldenrein 2008:42–43; see below).

While top-down approaches that rely on distant proxy data provide broadscale context, they do not provide the level of bottom-up local-scale detail necessary to evaluate the nature of regional dynamics across a large and ecologically varied expanse. Arguably, such resolution is essential for establishing the nuances of local climatic and environmental conditions and whether human societies of the past were willing, able, or even required to respond to pressures and threats.

Given that the Indus Civilization spanned a large and environmentally diverse area, it is unlikely that climate change would have had identical or even comparable effects in all regions. Similarly, hydrological shifts that may have been devastating in one area might have had no direct impact in others or may even have been beneficial. Furthermore, human behavior was likely already adapted to ecological regimes that are intrinsically variable between seasons and between years (see Wright 2010:25–44, 312–313, 315–319). Comprehension of the interrelationships between past climate and environment and human actions and reactions can result only from integrated approaches and collaborative research projects that seek to identify the interconnections between the archaeological evidence and the evidence for climatology, hydrology, sedimentology, and even ethnography, which are fundamentally interrelated but are too often treated as independent data sets.

This paper integrates research carried out as part of the *Land, Water and Settlement* project, which conducted collaborative work in northwest India between 2007 and 2014 (<http://www.arch.cam.ac.uk/rivers/>). It reviews the evidence for environmental diversity in northwest South Asia, assesses the ramifications of recently obtained data on the ancient hydrology and climate of northwestern India, and presents new archaeological evidence relating to geomorphology, settlement



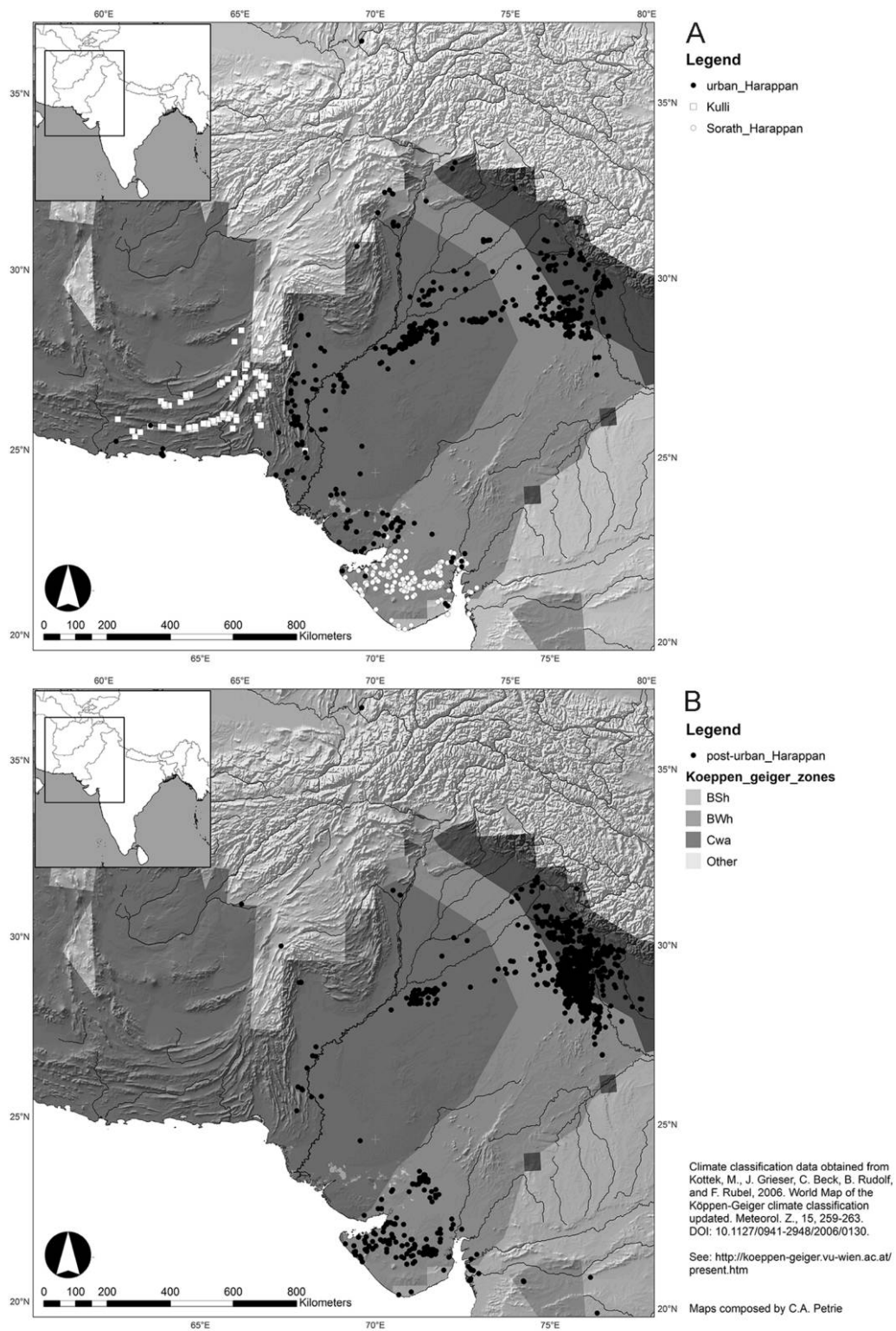


Figure 2. Distribution of urban-phase Indus settlements (A) and post-urban-phase Indus settlements (B) and their relationship to Global Köppen-Geiger Climate Classification Zones.



dynamics, the use of material culture, and subsistence practices in this region. Although coming from one of several regions occupied by Indus populations, these data necessitate the reconsideration of many prevailing views about the Indus Civilization as a whole, and this paper aims to further invigorate discussion about human-environment interactions and their relationship to processes of cultural transformation.

### Factors Influencing Environmental Diversity in Northwest South Asia

As noted above, the area across which Indus Civilization populations lived spans an environmental threshold characterized by a zone of overlap between winter and summer rainfall systems and steep rainfall gradients for both systems. This particular location spans a range of distinct ecological zones, with modern Köppen-Geiger Climate Classifications (Kottek et al. 2006) ranging from areas of arid hot desert (*BWh*) to areas of arid hot steppe (*BSh*) and areas that are warm and temperate with dry winters and hot summers (*Cwa*; fig. 2A, 2B). An important consequence of this environmental context is that even without human interference, water is available from different sources at different times of the year, including winter rain (December–February), rain from the Indian summer monsoon (June–September), snowmelt from the Himalayas, and the surface and river runoff that results from all of the above.

The lack of systematic and localized paleoclimatic data means that it is not yet possible to fully reconstruct the distribution of rainfall at the time of the Indus Civilization (see below). To frame our understanding, however, it is instructive to look at modern rainfall patterns to gain some insight into the nature of rainfall variability across the same geographic region. Plotting annual rainfall averages calculated using global rainfall data for the period between 1900 and 2008 illustrates that over the past century, different areas in northwest South Asia received different amounts of rainfall during an average year, ranging from 0 to 1,000 mm (fig. 1A, 1B). In addition, there is also variation in the seasonal distribution of modern rainfall (figs. 3A, 3B, 4A, 4B). The summer monsoon makes the dominant contribution to the average annual rainfall in many areas of the Indus zone, particularly those to the east, although a significant proportion of summer rain is lost through evapotranspiration. In contrast, the extensive areas of Punjab and Sindh that lie along the Indus and the rivers of Punjab receive rainfall in different intensities and at different times during the year. To further complicate matters, the historical record shows dramatic interannual fluctuations in the intensity of monsoon rainfall, with years of particularly heavy rainfall resulting in flooding and waterlogging interspersed with years of monsoon failure (Adamson and Nash 2013; Possehl 1999: 286–287; Sarma 1976).

While this assessment of modern rainfall patterning is informative, it cannot be assumed that the seasonal rainfall fell in similar patterns in the past. On the basis of analysis of sediments at the mouth of the Indus River, Staubwasser and

Weiss (2006) suggested that the mid-Holocene was characterized by high intra-annual rainfall variability in an increasingly arid climate, but we have little comprehension of the nature of this variability on the ground. Wright, Bryson, and Schuldenrein (2008) have used macrophysical climate modeling to make predictions about the intensity of summer and winter rainfall at Harappa between 14,000 BC and AD 2000. They modeled a protracted period of reduced rainfall between ca. 2100–1600 BC, which corresponds to the period of Indus urban deterioration and was attributed to a reduction in both winter and summer rain. Wright, Bryson, and Schuldenrein (2008) make it clear, however, that it is not feasible to extrapolate this record to other regions within the Indus zone (see also Balbo et al. 2014).

It is important to remember that beyond rainfall itself, an abundance of perennial and ephemeral rivers and streams redistribute water coming from the winter rains, snowmelt, and summer monsoon, and these all influence the hydrological systems of the Indus zone (Flam 1993, 1999, 2013; Jorgensen et al. 1993; Wright, Bryson, and Schuldenrein 2008). Furthermore, in addition to rainfall and hydrology, there is variation in the underlying geology, soils, and geomorphology, and similar degrees of variation invariably existed in these elements in the past (e.g., Belcher and Belcher 2000; Schuldenrein, Wright, and Khan 2007).

The available data thus indicate that the region inhabited by Indus populations was marked by considerable diversity in the distribution of winter and summer rainfall and variation in the quantity and intensity of rainfall in any one season in any one year. The Indus zone is thus “predictably unpredictable” in multiple ways. The variation in water supply combines with significant variation in hydrology and soils to create a broad zone comprising numerous ecological niches. All of these parameters enabled and/or constrained the types and range of subsistence practices that were possible and thus frame our understanding of Indus adaptation and resilience to climate change and the relationship of these factors to Indus urban decline.

### Coping with Environmental Diversity

Within the broader context of overlying environmental variability driven by climatic gradients, it is clear that Indus populations also occupied a diverse range of ecological niches or habitat zones. The Indus Civilization has long been regarded as riverine (e.g., Marshall 1931), and while many major Indus settlements were located close to rivers (e.g., Harappa, Mohenjo-daro, Lothal), others were located in intermontane valleys (e.g., Dabar Kot, Periano Ghundai) or on alluvial fans (e.g., Nausharo and Ghandi Umar Khan) at the margins or inside of what are today arid zones (sites in Sindh, Cholistan, and Gujarat), in areas that lack perennial rivers but are watered by monsoon rainfall (sites in Haryana and east Punjab), and even on islands (e.g., Dholavira; Petrie 2013; Petrie and Thomas 2012; Wright 2010:33–38).

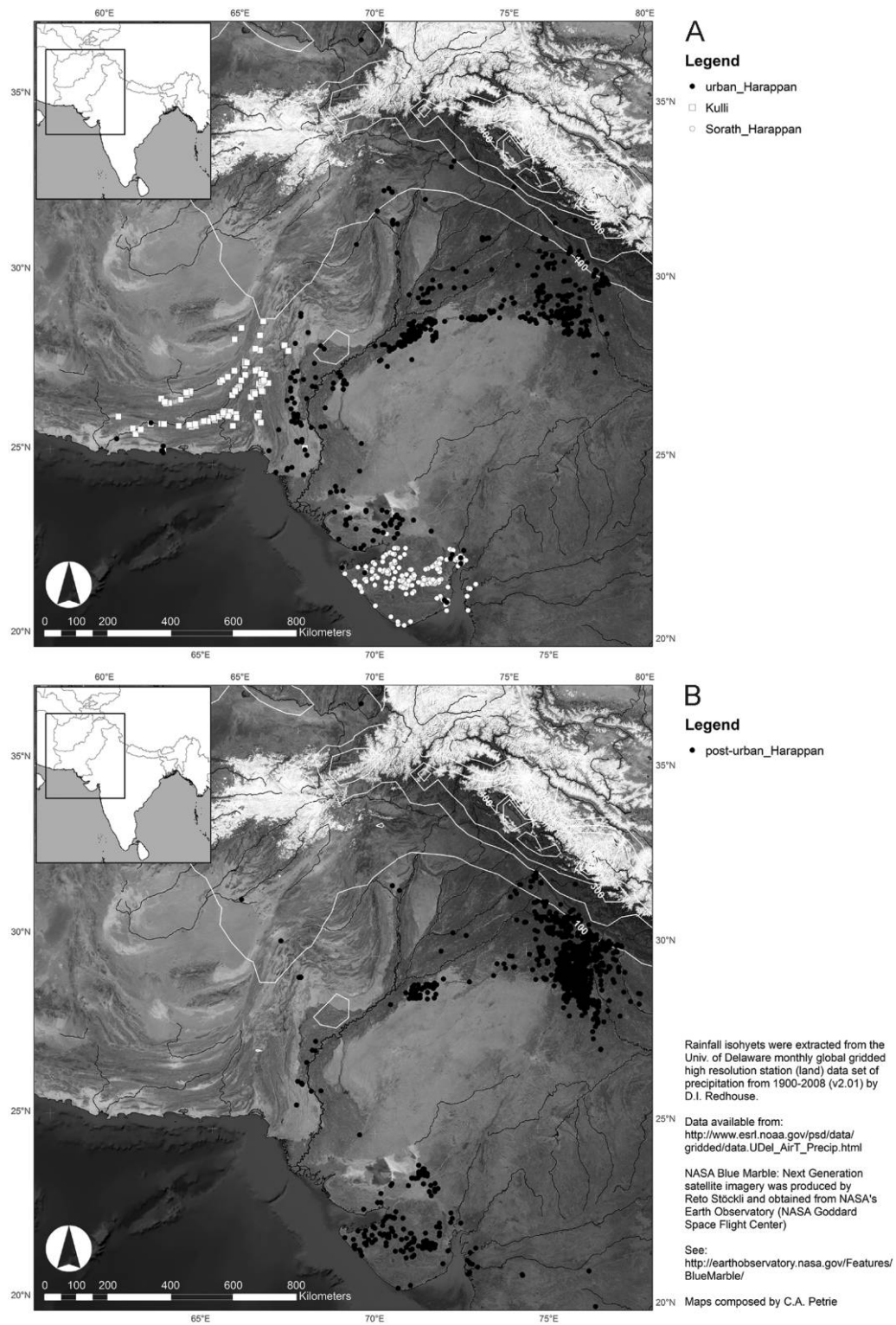


Figure 3. Distribution of urban-phase Indus settlements (A) and post-urban-phase Indus settlements (B) and their relationship to mean winter rainfall (1900–2008). A color version of this figure is available online.

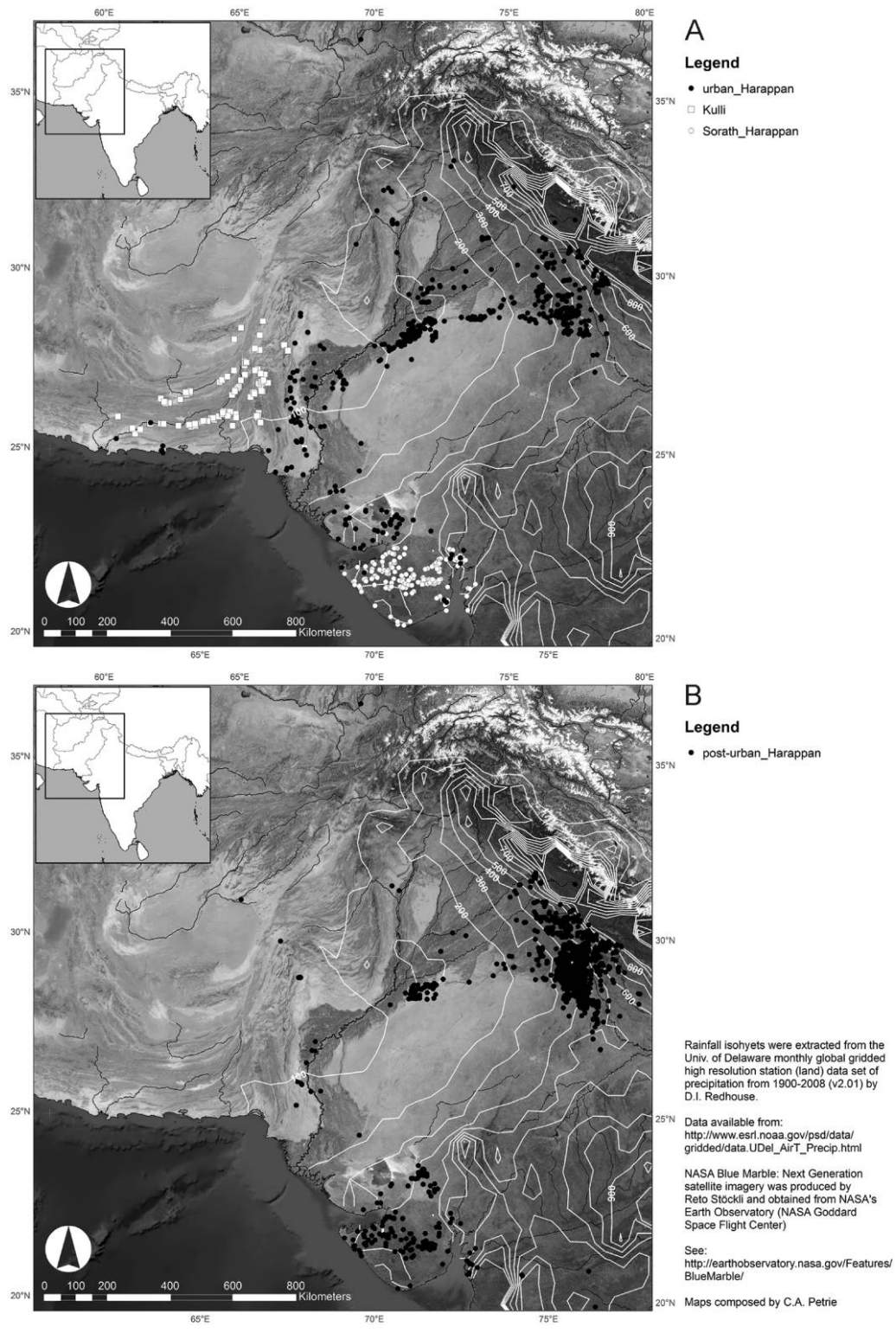


Figure 4. Distribution of urban-phase Indus settlements (A) and post-urban-phase Indus settlements (B) and their relationship to mean summer rainfall (1900–2008). A color version of this figure is available online.



It is notable that each of the Indus cities was supported by a different hydrological regime. Harappa, Ganweriwala, and Mohenjo-daro are in areas on the alluvial Indus plain that differ from each other in amounts of rainfall and proximity to major watercourses that provide water from both nonlocal rainfall and snowmelt in the Himalayas. Mohenjo-daro also has evidence for the extensive use of wells (Jansen 1993, 1994: 270), and examples are also known from elsewhere, including Harappa (Kenoyer 2008) and Dholavira (Bisht 2005, n.d.: 138–145). It is presumed that in each of these instances, the inhabitants exploited both river water and groundwater. In contrast, Rakhigarhi lies at some distance from known watercourses but is in the zone where both summer-monsoonal and, to a lesser extent, winter rainfall systems operate today. It has been proposed that Rakhigarhi lay on the course of a now extinct watercourse, which is often referred to as the Drishadvati (Nath 1998; Suraj Bhan 1975:95–101; Valdiya 2002). However, no evidence for this watercourse is visible today on the surface (Singh et al. 2010*b*), and analysis of the satellite imagery suggests that only small-scale watercourses are preserved in the subsurface (Mehdi et al. 2016, figs. 2, 10). It is not yet clear where the water used by the inhabitants of Rakhigarhi originated, though a combination of wells and ponds that collect monsoon runoff is a viable option (Petrie 2013). Dholavira is located in an area that today receives relatively limited rainfall but is close to two seasonal streams or runnels and has a system of dams that help channel water into a series of large stone-lined reservoirs and tanks, all of which presumably helped compensate for the unpredictable water supply (Bisht 2005, n.d.:138–169). Recognition of this diversity in settlement location and availability of water is essential for understanding both adaptations to different environments and responses to environmental challenges in the Indus context.

It has long been hypothesized that there was variation in the subsistence practices used by Indus populations (e.g., Chakrabarti 1988; Vishnu-Mittre and Savithri 1982), and this fits with the theme of coping with diverse environments. Although primarily speaking about Sindh and Baluchistan, Fairervis (1967:10, 42, 1971:169–172, 228–232) argued that Indus farmers were adapted to the diverse environments that they inhabited, particularly in terms of the adapting practices to the available water resources. Speaking more broadly, Possehl (1982, 1992) and Joshi (1984) have both posited the existence of ecocultural domains. More recently, models have been proposed for helping to identify Harappan agroecological zones, and several distinct ecozones have been identified (Weber, Barela, and Lehman 2010). However, robust evidence to support these suggestions is not widely available. For instance, Wright (2010) has pointed out that the archaeobotanical evidence that informs us about Indus populations is “uneven and dependent upon limited excavation” (170).

Indus agriculture is typically characterized as being dominated by the exploitation of a particular set of animals (primarily zebu, goat, sheep, and water buffalo) and a range of winter and summer crops (Meadow 1996; Weber 1999; Wright 2010:168–170). The exploitation of particular crops appears

to have been variable, and it has often been argued that two broad zones can be differentiated, with the predominant use of winter crops (*rabi*—wheat, barley, pea, lentil, chickpea) in some areas and the predominant use of summer crops (*kharif*—millet, rice, tropical pulses) being evident in others (Fuller 2006, 2011; Fuller and Madella 2001; Kajale 1991:173; Madella and Fuller 2006; Meadow 1996:398–400; Pokharia, Kharakwal, and Srivastava 2014; Weber 1999:818–822, 2003: 180–185; Weber and Kashyap 2016:9, 11, fig. 1; Weber, Kashyap, and Harriman 2010:36–37, fig. 1; Wright 2010:169–170). It is also asserted that there was an increased use of summer crops from the beginning of the second millennium BC onward, and Wright (2010:43) has suggested that this agricultural diversification may have been a response to ecological challenges.

Variation in practices is typically presented through comparison of Harappa in Punjab, which shows the predominant use of the winter cereals barley and wheat and the limited use of summer crops such as millets (*Panicum*) in what has been described as a complex multicropping system (Weber 2003: 181), and Rojdi and Babar Kot in Gujarat, which show an almost complete focus on summer crops (e.g., Reddy 1997, 2003; Weber 1991, 1999:816–818; Weber and Kashyap 2016; Weber, Kashyap, and Harriman 2010; Wright 2010:169–170; see also García-Granero et al. 2016). Winter and summer crops have been reported from several sites in northwest India, including rice and millet from preurban/Early Harappan period contexts at Banawali, Balu, and Kunal (e.g., Saraswat 2002; Saraswat and Pokharia 2002, 2003; Saraswat et al. 2000). It has, however, been argued that these attestations should be discounted because of a lack of quantification in the final publications, and a lack of direct absolute dates (e.g., Fuller 2006: 13, 16; 2011; see Petrie et al. 2016). Furthermore, winter and summer crops are also seen at Farmana in northwest India, though rice is not present in the stratified contexts, but the significance of this is difficult to interpret as only presence and absence information for macro- and microbotanical remains are provided, alongside summative figures for seed density and ubiquity (Kashyap and Weber 2013; Weber and Kashyap 2016; Weber, Kashyap, and Mounce 2011, tables 11.1, 11.2).

Given that we lack published quantified assemblages from most Indus sites where archaeobotanical analysis has been carried out, it is likely that interpretations based on contrasting Harappa and sites in Gujarat are too simplistic. The problems are partly related to coverage but also interpretation. For instance, as noted above, it has been argued that the cropping system at Harappa was a complex multicropping strategy (Weber 2003), which may have been a response to ecological challenges (Wright 2010:43). The published evidence that includes quantification (e.g., Weber 2003), however, suggests relatively restricted use of crops grown in the nondominant season. It could thus be argued that such low proportions of summer crops do not actually indicate extensive multicropping (Petrie and Bates, forthcoming; Petrie et al. 2016). Petrie and Bates (forthcoming) and Petrie et al. (2016) have, there-



fore, argued that while the archaeobotanical assemblages thus far published do demonstrate regional variation in subsistence practices (e.g., García-Granero, Lancelotti, and Madella 2015; Weber 1999, 2003; Weber, Barela, and Lehman 2010; Weber and Kashyap 2016), they have not (yet) provided convincing evidence from any single location for cropping in two seasons in anything approaching equivalent proportions (see below). They thus advocate the use of more precise terminology to characterize the variation that is observed (Petrie and Bates, forthcoming).

Although Indus populations may well have selected specific plant crops, the degree of variation in local environmental conditions, vegetation, rainfall, and water supply would invariably have necessitated specific adaptations to farming practices for successful farming in different regions. These adaptations would likely have included a range of approaches to water supply (cf. H. M.-L. Miller 2006, 2015; Petrie and Thomas 2012) and a spectrum of cropping strategies ranging between a heavy focus on winter or a heavy focus on summer crops, with the middle ground being made up of a nuanced array of strategies where different combinations of winter and summer crops were utilized according to local conditions and choices (Petrie and Bates, forthcoming; also Petrie 2013; see below).

It is clear that the degree of ecological diversity encompassed by the Indus Civilization and the variability of adaptation and response across that area is critical for understanding the developments of the Indus period. However, the diversity in socioecological systems can be characterized adequately only by detailed research in each of the relevant zones. This research has only recently begun to be carried out at a suitable resolution. In Pakistan, the most important contributions have come from the Sindh Archaeological Project (Flam 1993, 1999, 2013; Jorgensen et al. 1993) and the Beas Landscape and Settlement Survey (Schuldenrein, Wright, and Khan 2007; Wright 2010; Wright, Bryson, and Schuldenrein 2008; Wright and Hritz 2013; Wright, Khan, and Schuldenrein 2002, 2005a, 2005b), while in India, knowledge is advancing most overtly in Gujarat through the North Gujarat Archaeological Project (Balbo et al. 2014; García-Granero et al. 2016; Madella et al. 2010) and in Haryana/Punjab/north Rajasthan through the *Land, Water and Settlement* project and the earlier Mission Archéologique Française en Inde (Courty 1985, 1995; Courty, Goldberg, and Macphail 1989; Francfort 1985; Gentelle 1985). The evidence gathered by the *Land, Water and Settlement* project will be explored further below, covering five key areas: monsoon dynamics, the paleo-Ghaggar/Hakra, monsoon flooding, settlement dynamics, and variation in material culture and subsistence.

### Changes in Intensity of the Indian Summer Monsoon during the Holocene

The significant environmental variability of the Indus region and the apparent flexibility of Indus populations in coping

with this range of environments both form a critical backdrop to debates about the impacts of climate change. As noted above, until recently, however, debates about the impacts of climate change on Indus populations have been hampered by a lack of direct and proximate climate data. Proximate data is essential for establishing whether there was any local impact of globally detectable climate change on the plains of northwest South Asia during the Holocene.

New proxy records have been collected from within the Indus zone as part of the *Land, Water and Settlement* project, and these inform understanding of variation in the climate affecting Indus populations. The most relevant is the climate proxy record from Lake Kotla Dahar in southern Haryana (fig. 1A, 1B), which indicates that there were two distinct shifts in rainfall distribution and intensity during the mid-late Holocene that affected northwest India (Dixit, Hodell, and Petrie 2014). In the early Holocene, Kotla Dahar was a deep lake, implying regular and consistent rainfall input to offset evaporation, which given its location, would have been primarily monsoonal (Dixit, Hodell, and Petrie 2014). The first shift occurred at some point between ca. 4400 and 3760 BC (ca. 6400–5760 BP), when there was a decrease in monsoon rainfall and a progressive lowering of the lake level. This initial shift is roughly coincident with the evidence for change from Didwana (Zone D5) and Lunkaransar (Zone 3) lakes in Rajasthan, though there are no reliable dates for the transitions at either (Enzel et al. 1999; Madella and Fuller 2006; Prasad and Enzel 2006). The second of these changes is more directly relevant, as it shows Kotla Dahar becoming completely ephemeral ca. 2200–2000 BC (ca. 4100 ± 100 BP) as a result of an abrupt weakening of the monsoon (Dixit, Hodell, and Petrie 2014). This shift in the monsoon is visible as a 300 ± 100-year event in speleothem records in Oman (Fleitmann et al. 2003) and northeast India (Berkelhammer et al. 2012) and appears to match a change in levels of discharge from the Indus between ca. 4200 and 3600 BP (Staubwasser et al. 2003). The Kotla Dahar evidence indicates that the shift in the intensity and extent of monsoon rainfall specifically in northwest India was both dramatic and protracted, resulting in an ephemeral lake that continues to the present (Dixit, Hodell, and Petrie 2014).

The degree to which the data from Kotla Dahar might be extrapolated to other parts of the Indus zone is debatable, and the relationship between climate and culture change remains ambiguous. It is nonetheless tempting to highlight correlations. The weakening in monsoon strength ca. 2200–1900 BC appears to correlate broadly with both the maximum extent of occupation at Mohenjo-daro and Harappa and the onset of Indus urban decline, though this was not a uniform process (e.g., Wright 2010:43). The chronological correlation between the data sets is, however, imprecise due to the limitations of radiocarbon dating techniques in terms of precision (Dixit, Hodell, and Petrie 2014; Staubwasser and Weiss 2006).

The Kotla Dahar proxy record suggests that climate must be formally considered as a contributing parameter in the process of Indus deurbanization, at least in the context of the plains of northwest India. This is, however, inevitably only

part of the story, and it is the human response to this change in climate that is the critical element. For example, it has been suggested that decline in monsoon strength led to the diversification of the Indus crop assemblage through the adoption or intensified use of more summer crops such as millet and rice (Giosan et al. 2012; Madella and Fuller 2006; Wright 2010:321ff.). This reconstruction is perhaps overly simplistic, as it advocates the greater exploitation of summer crops at a time when the summer rainfall weakened, and it does not consider the different lengths of growing seasons required for millet and rice or the fact that each of these crops is suited to somewhat different ecological conditions. It has also been at least partly superseded by new evidence that gives fresh insight into the nature of environmental adaptation that Indus populations engaged in even before the development of urban centers (see below).

### The Role of the Paleo-Ghaggar/Hakra River in Northwest India

Alongside the considerations of climate and climate change, there has been considerable discussion of the role of the paleo-Ghaggar/Hakra River in the origin, floruit, and transformation of the Indus Civilization. It is often suggested that this paleochannel provided an important source of water for Indus populations living in various areas (e.g., Danino 2010; Kenoyer 1997; Lal 2002; Mughal 1997; Tripathi et al. 2004; Valdiya 2002; Yash Pal et al. 1980). However, the lack of dates for the perennial flow of water in this paleochannel and the lack of clarity about the source of that water means that this claim is largely speculation.

Although traces of a paleochannel were observed on the ground in Rajasthan and Punjab in the nineteenth century, today it is primarily known thanks to a large linear feature visible on satellite imagery (Bhadra, Gupta, and Sharma 2009; Yash Pal et al. 1980). Analysis of sections exposed in wells and electrical resistivity surveys in various locations along the paleo-Ghaggar/Hakra in northwest India have suggested that this feature was one or more large relict river channels (Saini et al. 2009; Sinha et al. 2013; Mehdi et al. 2016).

There have now been several attempts to date the flow of perennial water through these paleochannels, in both Pakistan and India. There is growing consensus that the major paleochannel ceased to be a perennial watercourse before the Holocene (Clift et al. 2012; Giosan et al. 2012; Lawler 2011:23; Saini et al. 2009). However, there is some evidence of water flowing through various channels during the mid-Holocene (Clift et al. 2012; Giosan et al. 2012; Maemoku et al. 2012; Saini et al. 2009; Shitaoka, Maemoku, and Nagatomo 2012) and ongoing debate about whether the paleo-Ghaggar/Hakra was an earlier course of the modern Sutlej (Lawler 2011:23) or an earlier course of another river, perhaps the Yamuna (Clift et al. 2012).

Despite being visible on satellite imagery, the fact that a large river channel is not visible on the ground in many areas

demonstrates that there has been a considerable alluviation in the channel since perennial flow ceased. The precise subsurface architecture of the paleo-Ghaggar/Hakra and Punjab hydrological systems, the date at which particular channels carried perennial water, and the source of that water continue to be debated, but there is a real possibility that the paleo-Ghaggar/Hakra did not carry water perennially during the Indus period. If this is true, it has profound implications for interpretations of the importance of this hydrological system for Indus populations, not least because it means that while water continued to flow through the paleo-Ghaggar/Hakra seasonally, it was not a perennial river in the centuries before, during, or after the Indus Civilization.

Taken together, the new data stand in contrast to a range of historical attestations to the existence of a mighty perennial river along this course in northwest India (e.g., Chakrabarti and Saini 2009; Danino 2010). It is, however, important to point out that the extant documentary records are unlikely to conform neatly to modern distinctions between ephemeral and perennial water flow. What might have appeared as a mighty river in times of monsoon-induced spate may have been dry at other times of the year. If the water flow in the modern Ghaggar is any indication, rivers in this environment can be virtually empty for much of the year and full to overflowing during the monsoon.

Perhaps more importantly, the watercourse need not have been perennial to have been important for the ancient inhabitants. The new data suggest that the settlements along the course of the paleo-Ghaggar/Hakra such as Kalibangan, Banawali, and Bhirrana were not sited to exploit a perennial river but to gain access to water via reliable annual monsoon runoff and overbank flooding. Water was undoubtedly exploited for different purposes when it was available and captured and stored for use at other times, and it is likely that the paleo-Ghaggar-Hakra was important during the Indus period for reasons that are quite different to those usually claimed. Overall, the likelihood that the paleo-Ghaggar/Hakra was not a perennial river has important implications for the way in which Indus populations were adapted to a diverse and variable environment and the type of responses that were needed when that environment changed dramatically.

In addition to its implications for understanding Indus settlement systems in northwest India, the possibility that the paleo-Ghaggar/Hakra did not carry perennial water is particularly significant for understanding the evidence for extensive Indus settlement in Pakistani Cholistan. Giosan et al. (2012) have suggested that “reliable monsoon rains were able to sustain perennial rivers earlier during the Holocene,” which “explains why Harappan settlements flourished along the entire Ghaggar-Hakra system without access to a glacier-fed river” (3). However, the monsoon is unlikely to have provided a sustained source of water throughout the year; instead it produces a charge between June and September to the hydrological system that may have otherwise been dormant. Rather

than seeking to explain the Cholistan settlement concentration by proposing that summer monsoon rainfall is capable of supporting perennial river flow, an alternative possibility is presented by a critical reexamination of the dynamics of the Cholistan settlement system.

As published, the Cholistan survey data show that there were considerable numbers of sites occupied in the preurban, urban, and posturban Indus periods, each of which were up to five centuries in duration (Mughal 1997). As is true for many regions of the world, it is assumed that settlements were occupied for the entirety of each period. Unfortunately, we know very little about the lifeways of the people living in these settlements as no excavations have been published, and we have no robust data on local subsistence practices, geomorphology, or hydrology. We do know, however, that very small numbers of the Indus settlements were occupied in consecutive periods and that, in each period, settlements were concentrated in different parts of the survey area. Use of the Dewar algorithm (1991) to assess settlement contemporaneity in the Cholistan data has suggested there is a reasonable statistical likelihood that as few as 5%–10% of settlements may have been occupied contemporaneously during the preurban, urban, and posturban periods (Petrie and Lynam, forthcoming). In contrast, using the same algorithm to analyze the data from the Rakhigarhi Hinterland Survey from northwest India reveals a significantly high degree of contemporaneity of occupation at settlements during the preurban, urban, and posturban periods in that region (75%; Petrie and Lynam, forthcoming). These data suggest that it may be a mistake to assume that the large numbers of settlements recorded for each phase in Cholistan represent concentrated and dense settlement. Rather, Cholistan may have been characterized by an unstable settlement system with little continuity of occupation between periods at individual settlements, and only a subset of settlements may have been occupied at any one time.

While this suggestion is provocative, we currently lack the data to determine whether it is sound, and the river systems of Cholistan undoubtedly require further detailed investigation. Instability in the Cholistan settlement system may have been a product of the operation of a braided river system, which would have been susceptible to the frequent small-scale avulsions during the periods of flooding that occur during monsoon rains. Such an environment may have required settled populations to be relatively mobile in order to survive a constantly shifting hydrology, and there may have been high population mobility between settlement locales. Individual families or kin groups potentially spread their members between multiple settlements, and individuals or groups might have moved between settlements to access available water in times of shortage or stress. Such practices clearly have implications for our understanding of the degree to which Indus populations were adapted to a diverse environment and the sustainability and resilience of those adaptations.

## Geomorphological Evidence for Monsoon-Induced Annual Flooding

The recent data from Kotla Dahar and the paleo-Ghaggar/Hakra are congruent with the results of systematic geomorphological analysis of the context of Indus settlements on the plains of northwest India by the *Land, Water and Settlement* project. Analysis of soil and sediment samples taken adjacent to settlements lying in two areas along the paleo-Ghaggar/Hakra in central Harayana (Burj, Bhirrana, and Banawali) and northern Rajasthan (Dabli-vas Chugta and Kalibangan) has shown that, during the Holocene, the lower-lying areas in the landscape were probably more or less continually subjected to the slow, low-energy seasonal deposition of overbank flood deposits composed of fine sand and silt (fig. 5A, 5B; French, Sulas, and Petrie 2014; Neogi 2013; Singh et al. 2010a, 2012). These sediments are composed of very fine micaceous sands and silts, suggesting low energy water transport, and were presumably deposited by runoff associated with monsoonal rains and riverine overbank flooding, which lead to the seasonal aggradation of alluvium (Giosan et al. 2012; Singh et al. 2010a, 2012). This reconstruction appears to correlate with Clift et al.'s (2012) reconstruction of the mid-late Holocene Sutlej and Yamuna River drainage and Flam's (1993, 1999, 2013) analysis of sedimentation in Sindh.

Today areas along and adjacent to the paleo-Ghaggar are subject to flooding and associated sedimentation during the monsoon. The new geomorphological evidence from the *Land, Water and Settlement* project suggests that this process has been active for some time and was undoubtedly important for Indus farmers in this region (French, Sulas, and Petrie 2014; Neogi 2013; Singh et al. 2010a, 2012). In turn, this has important implications for considerations of the impacts of climate change. The weakened summer monsoon in northwest India after ca. 2200 BC attested at Kotla Dahar would have resulted in, at minimum, a reduction in the intensity of that rainfall, which in turn will have decreased the amounts of annual overbank flood-induced sedimentation and erosion. Monsoon weakening will thus inevitably have had consequences for farmers relying on overbank flooding to water summer crops and the concomitant stored soil moisture essential for the establishment of winter wheat and barley.

## Settlement Distribution Data

To contextualize the new understanding of rainfall distribution, climate change, hydrology, and geomorphology in northwest India, the *Land, Water and Settlement* project has also carried out extensive investigation of the settled landscape of this region. There is a sizable body of evidence for the distribution of preurban, urban, and posturban Indus settlements throughout Pakistan and northwest India (e.g., Joshi, Bala, and Ram 1984; Kumar 2009; Possehl 1999). These data have been used to build models of long-term sociocultural change



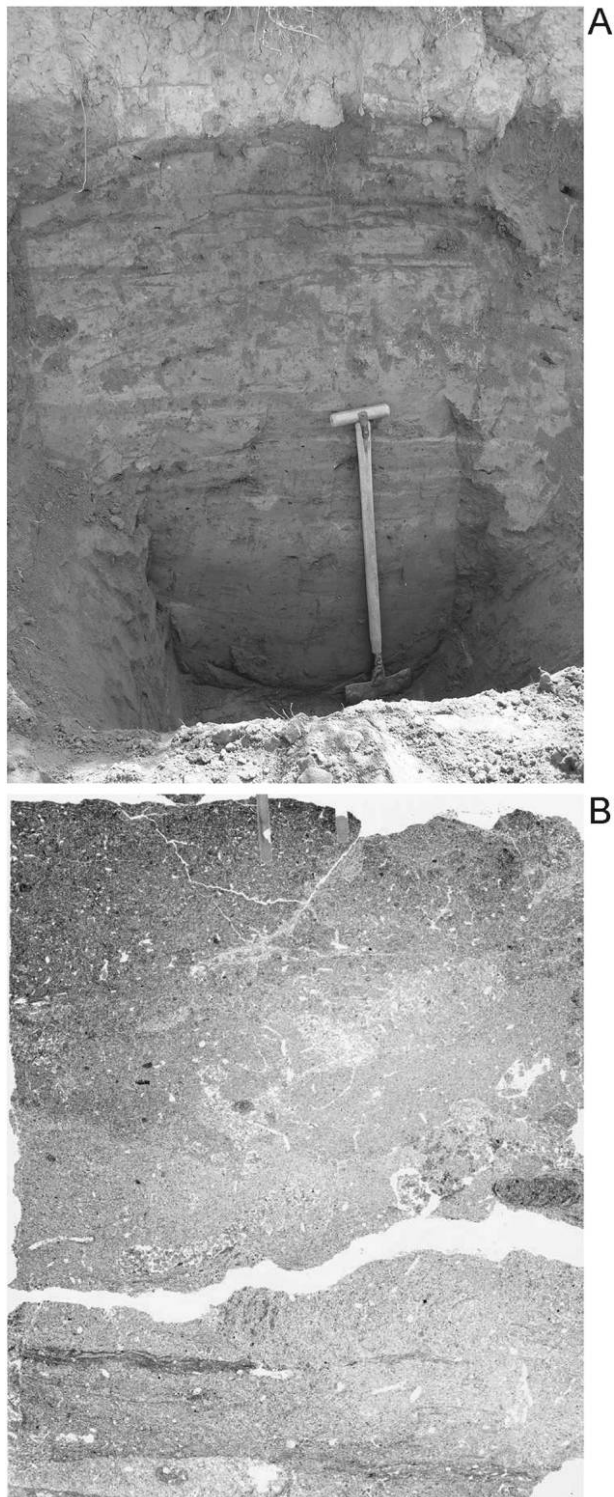


Figure 5. *A*, Geomorphology at Masudpur I showing an alluvially thickened, organic sandy-silt-buried soil horizon situated beneath ca. 1 m of archaeological deposits. *B*, Close-up of a micromorphological slide taken from this section. A color version of this figure is available online.

and highlight a potential shift of settlement toward the Ganges plains in the wake of the decline of the Indus urban centers (Giosan et al. 2012; Joshi, Bala, and Ram 1984; Madella and Fuller 2006).

The limitations of the core data set have, however, typically been overlooked. Detailed surveys in northwest India by the *Land, Water and Settlement* project have demonstrated that a significant proportion of these data are fundamentally unreliable. Both reconnaissance and detailed surveys have shown that there are significant errors in the published locations of many sites, highlighted that the knowledge of site distribution and density is dictated by the intensity and extent of previous surveys, and established that large numbers of sites of all periods have not been recorded (Pawar 2012; Singh et al. 2008, 2010*b*, 2011). These realizations have several important implications; for instance, it has frequently been stated that there is a close spatial correlation between the paleo-Ghaggar/Hakra and the distribution of Indus settlements and that there is a profusion of Indus sites along this channel in the area to the east of Kalibangan (e.g., Danino 2010; Lal 2002; Valdiya 2002). The Rakhigarhi Hinterland Survey (Singh et al. 2010*b*) and Ghaggar Hinterland Survey (Singh et al. 2011) and compilations of other extant survey data (Kumar 2009) have revealed, however, that there are actually relatively few sites that lie directly along the course of the paleo-Ghaggar/Hakra for much of its course across northwest India (fig. 6*A*, 6*B*).

Despite its limitations, the extant survey data can be combined with the *Land, Water and Settlement* project results to show that urban and posturban Indus settlements were not specifically concentrated along any river channel but were, in fact, distributed across various parts of the plain. This distribution includes areas close to the paleo-Ghaggar/Hakra, areas adjacent to ephemeral watercourses and areas that have no relationship to any visible water sources, including the desert margin in northwest India (fig. 6*A*, 6*B*; Petrie 2013; Singh et al. 2008, 2010*b*, 2011). Although there is no clear evidence for a large paleochannel in the vicinity of Rakhigarhi, the possibility that there is a subsurface channel in this area cannot be discounted, though its age and precise course—and, hence, its relationship to the ancient settlements—will only be reconstructed through a targeted study to this end.

While there is general consensus that there was an increase in settlement in northwest India in the posturban Late Harappan period, this conclusion is almost entirely based on inferences arising from the aforementioned unreliable survey data. Importantly, the *Land, Water and Settlement* project surveys have shown that there was no increase in the number of village-sized settlements in the central part of the plains during the posturban phase, which implies that there was no substantial increase in the local population in these areas (Singh et al. 2010*b*, 2011). This observation suggests that if the perceived intensification of village settlement in northwest India during the posturban/Late Harappan period is real, then it was concentrated elsewhere, most probably in the areas that are warm and temperate with dry winters and hot summers (*Cwa*)



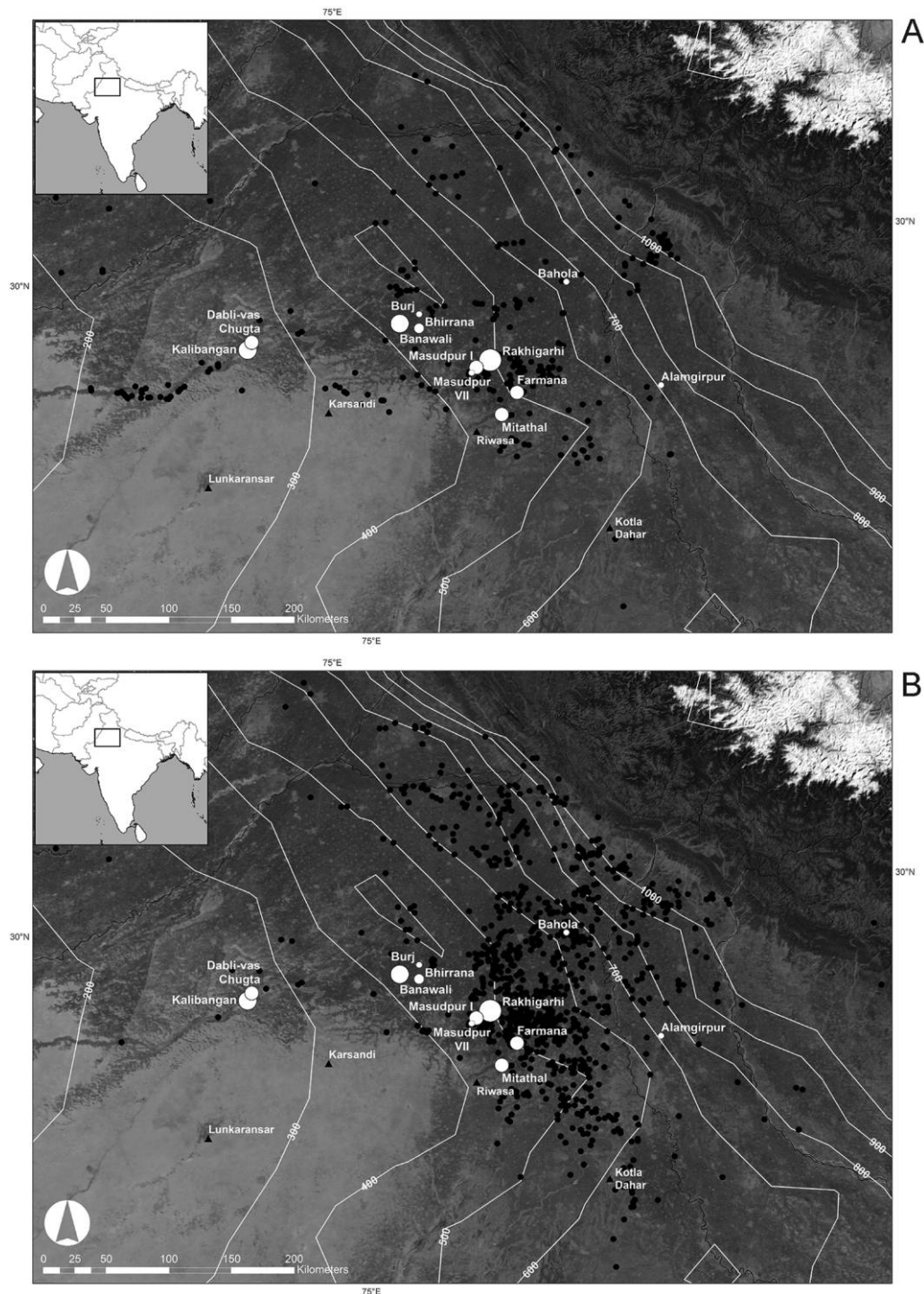


Figure 6. Distribution of urban-phase Indus settlements (A) and post-urban-phase Indus settlements (B) in northwest India and their relationship to mean annual rainfall (1900–2008). Major Indus sites and sites investigated by the *Land, Water and Settlement* project are shown in white. A color version of this figure is available online.

that lie along the Himalayan front and at the eastern edge of the plains (figs. 2B, 3B, 4B). Today these areas receive more than 300 mm of direct monsoon rain per annum (fig. 4B), which suggests that they are likely to have received some rainfall even during periods of weaker monsoon, though this remains to be

demonstrated. The cultural processes that led to this pattern of settlement have still not been examined systematically, and additional areas in Haryana and the broad region along the Himalayan front in both Pakistani and Indian Punjab need to be surveyed if the nature of settlement distribution is to be

properly understood. In particular, it needs to be determined whether and when specific habitats and environmental contexts were being selected preferentially.

This reassessment of the evidence for the distribution of settlements in northwest India suggests that the local Indus populations probably employed a range of approaches to land use, even before cities developed. Perhaps the key element is that for populations to have lived in such environmentally diverse areas, their agricultural systems must have been far more flexible and adaptive to local conditions than is usually acknowledged. In some areas of northwest India, rainfall may have been sufficient to grow crops without irrigation, while in others, various methods of low-cost irrigation or active water management (*bunds*, canals, etc.) may have been essential. It is thus likely that the ancient populations, in this area at least, made use of whatever water was available, whether it was from rainfall, runoff, and overbank flooding or water flow from streams and rivers (cf. H. M.-L. Miller 2006, 2015; Wright 2010:33–34). It is also likely that attempts were made to capture and store water in ponds and tanks and to access underground water using wells, as is prevalent among modern populations (Petrie 2013; Singh et al. 2008). Although canal-based irrigation is frequently dismissed as a contributing factor in Indus farming practices, Chakrabarti (1988, 1999:327) has long argued that it must have played a critical role (cf. Francfort 1992; Gentelle 1985, fig. 14). The identification of evidence for irrigation (or its lack) should be a priority of future research, and similarly, the role of ponds and tanks requires focused investigation, as both were potentially very significant during the Indus period.

### The Material Culture and Subsistence Practices of Village-Based Early and Mature Harappan Populations in Northwest India

Although there is clear evidence for the widespread use of a range of distinctive material culture items and practices during the urban phase of the Indus Civilization, it is arguable that the degree of material uniformity has been overstated (Petrie 2013). When excavations at Indus settlements are published, it is the typically classic Indus material (e.g., seals, beads, black-on-red decorated pottery) that is highlighted. However, a range of other cultural material is also recovered, and there are several instances where regionally distinct material, including decorated ceramic vessels and figurines, were produced and used locally. For example, excavations at the urban-phase site of Farmana in northwest India have shown that the population of this town-sized settlement predominantly used locally produced and distinctively decorated ceramic vessels (comprising 80% of the assemblage) and made relatively limited use of the more distinctive classic Indus ceramics well known from sites like Rakhigarhi, Kalibangan, Harappa, and Mohenjo-daro (Uesugi 2011:179ff.).

Excavations carried out as part of the *Land, Water and Settlement* project have deepened our comprehension of this

regionality. At the smaller, village-sized sites of Masudpur I and VII (fig. 7), which lie within the hinterland of Rakhigarhi, only region-specific styles of pottery were used during the urban phase, and no classic Indus types were recovered from either the surface or the excavations (fig. 8; Parikh and Petrie, forthcoming; Petrie, Singh, and Singh 2009). Other types of characteristically Indus material were present, however, including various types of beads and bangles (fig. 9A, 9B), suggesting that the populations of these settlements remained connected to the interactive networks that linked Indus populations more broadly. This evidence for regional variation supports the suggestion that the widespread attestation of classic Indus material is actually a veneer that overlay a considerable degree of cultural diversity (Meadow and Kenoyer 1997:139; Petrie 2013).

There is also evidence to suggest that a diverse crop assemblage and, thus, diverse subsistence practices were being used in northwest India well before the posturban period. The combined macro- and microscopic analysis of material from systematically recovered samples collected at Masudpur I and VII have revealed evidence for the exploitation of both summer and winter crops and, particularly, the preferential exploitation of millet (both *Echinochloa* cf. *colona* and *Setaria* cf. *pumila*), rice (*Oryza*), and a range of tropical pulses including mung bean (*Vigna radiata*), urad bean (*Vigna mungo*), and horsegram (*Macrotyloma* cf. *uniflorum*; fig. 10A, 10B; Bates

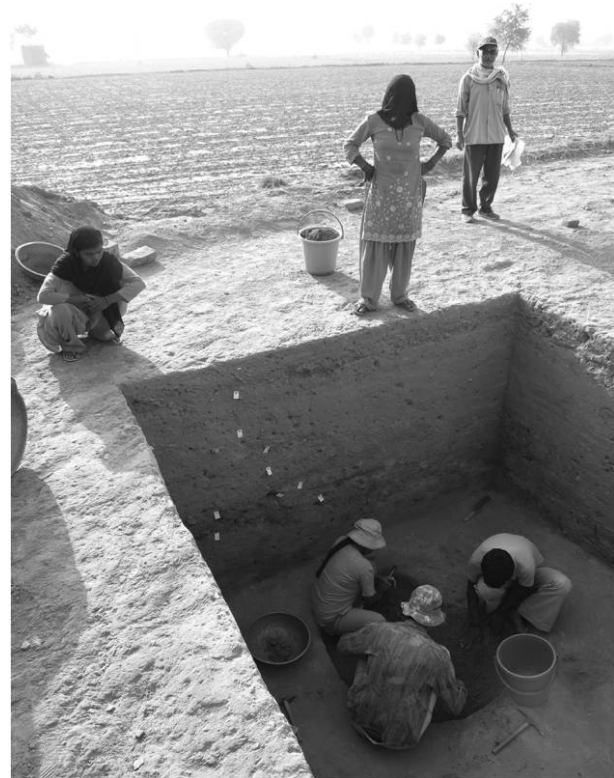


Figure 7. Excavations being carried out in Trench XA1, Masudpur I. A color version of this figure is available online.



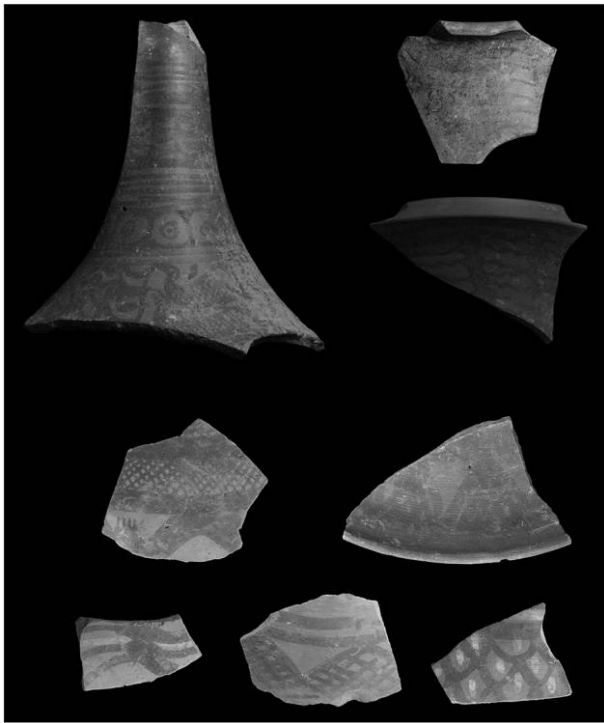


Figure 8. Classic Harappan ceramics from Farmana and local ceramics from Masudpur I and VII (after Uesugi 2009, figs. 6.126, 6.145, 6.161). A color version of this figure is available online.

2016; Petrie and Bates, forthcoming; Petrie et al. 2016). This discovery confirms earlier indications that these crops were being used in this region (Saraswat and Pokharia 2002, 2003) but goes further by dating their exploitation using both relative material culture indicators and direct accelerator mass spectrometry radiocarbon dates to the Early, Mature, and Late Harappan phases (Petrie et al. 2016). Millet appears to have been the dominant crop in all phases at both sites, and rice is the second-most abundant crop at Masudpur I, appearing in higher quantities and proportions than either wheat or barley (Bates 2016; Petrie and Bates, forthcoming; Petrie et al. 2016, tables S2, S3). These new dates confirm that summer crops were being used alongside winter crops before, during, and after the existence of the Indus urban center at Rakhigarhi, which is different to what is seen at Farmana (Weber, Kashyap, and Mounce 2011).

The excavations by the *Land, Water and Settlement* project thus confirm that there was diversity in material culture both between regions and between different types of Indus settlements within regions. They have also definitively demonstrated that different subsistence pathways involving combinations of winter and summer crops were used in different areas and that there was marked diversity in the crop assemblage within some regions before the Indus urban phase. They thus suggest that Indus populations in some regions were well adapted to living in diverse and changeable ecological and environmental conditions and were thus well placed to make sus-

tainable and resilient decisions in the face of environmental change. The choices that Indus populations made in the face of such change all potentially revolve around the consolidation of the rural/agrarian baseline and include deurbanization (and decentralization), simplification of craft practices, population displacement, and widespread adoption of diverse approaches to subsistence.

### Conclusions: Adaptation, Resilience, and Changing Perceptions of Indus Urban Decline

There is much to learn from investigating the archaeology of human adaptation, resilience, and response to climatic and environmental change and the adaptive and resilience strategies that complex sociopolitical systems may have to engage in to survive. If we are to understand how humans coped with climate change, it is important to understand how they were adapted to particular environments and whether those adaptations enabled populations to be resilient in the face of episodes of climate change. For most ancient complex societies, water is a critical factor, and the availability of water and the way that it is managed and used provide critical insight into human adaptation and the suitability and resilience of subsistence practices.

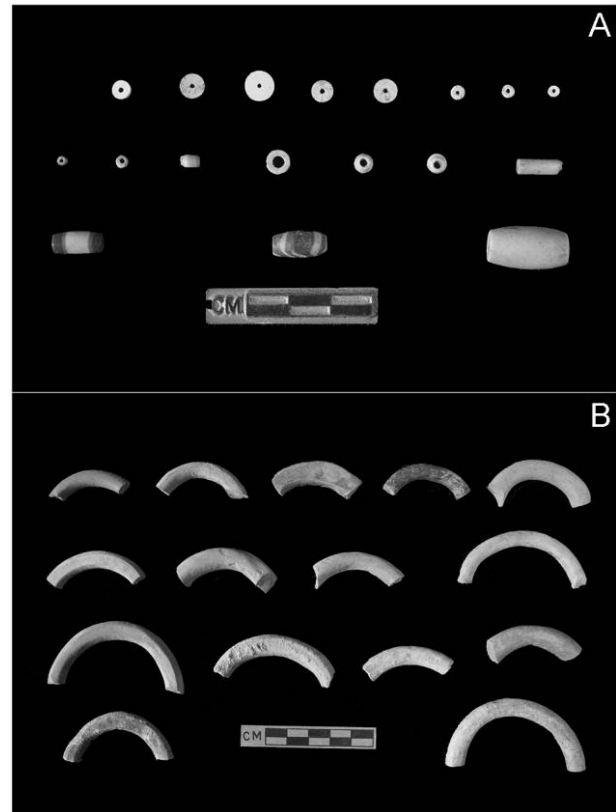


Figure 9. Indus material culture from Masudpur I and VII, including steatite, faience, and agate beads (A) and Indus-style ceramic bangles (B). A color version of this figure is available online.

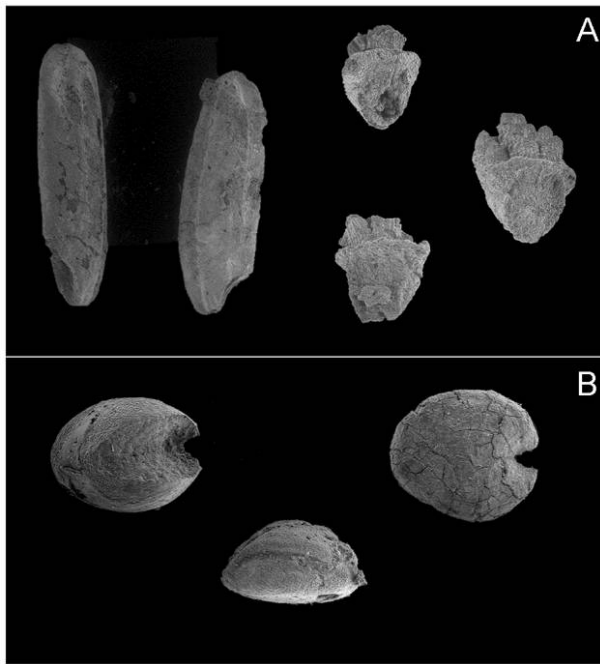


Figure 10. Carbonized crop grains from Masudpur VII, including carbonized rice grains (*Oryza*; A) and carbonized millet grains (*Echinochloa*; B).

This paper has outlined a wide range of new evidence that encourages the reconsideration of several aspects of the nature of the Indus Civilization, particularly the environmental and climatic context within which urbanism developed and, ultimately, declined. It is not yet possible to establish adequately how Indus populations responded to the change in rainfall patterns that affected the plains of northwestern South Asia ca. 2200–2100 BC. The evidence for climate change at a local scale indicates that there were clear changes to the patterns and intensity of summer rainfall in northwest India. Given the degree of environmental variation within the Indus zone and the range of adaptations to farming that were being used across it, it is likely that these changes in summer rainfall would have had a differential impact, with some regions feeling the change directly and perhaps acutely, while others would have been impacted indirectly, if at all. Ascertaining the nature of this differential impact is an obvious topic for future research.

The new archaeobotanical data produced by the *Land, Water and Settlement* project shows that models arguing that the collapse of Indus urbanism was caused by a shift in the summer monsoon (Staubwasser and Weiss 2006), which led to the diversification of the crop suite used, including the widespread adoption and/or more intensive exploitation of rice and millet (Giosan et al. 2012; Madella and Fuller 2006), are overly simplistic. They are also potentially paradoxical, as it was in northwest India that there appears to have been a reduction in the quantity of the summer rainfall needed to water these summer crops and potentially aid the growing of winter ones.

Rather than being forced to intensify or diversify subsistence practices in response to climatic change, the evidence from Masudpur I and VII for the use of millet, rice, and tropical pulses in the preurban and urban phases suggests that local Indus populations were already adapted to living in varied and variable environmental conditions before the development of urban centers. These environments are today marked by differences in ecology and are subject to considerable variation in rainfall patterns during individual years and between years, and similar patterns might reasonably be expected for the past. This pattern of ecological diversity and variable rainfall reinforces suggestions that different strategies must already have been adopted in different areas in response to different ecologies (Petrie 2013; Singh and Petrie 2009; Weber, Barela, and Lehman 2010; Wright 2010). This variation in approaches to subsistence is also matched by a hitherto underemphasized diversity in the nuances of cultural practices that have been at least partly masked by the overt and widely used veneer of distinctive (or classic) elements of Indus material culture.

Based on the work conducted by the *Land, Water and Settlement* project, we argue that it is this fundamental diversity in behavior, particularly in the proportional exploitation of winter and summer crops, that may have made it possible for populations in some areas to adjust to the dramatic weakening in monsoon rainfall after ~4200 BP/ca. 2200–2100 BC. We also argue that true insight into suitable strategies for surviving in variable environments that undergo change can come only by establishing the degree to which subsistence systems were adapted to local conditions and resilient to factors such as water stresses and the socioeconomic and political stresses that result from climate change. It will, however, only be possible to characterize the level of variation in subsistence practices across the Indus Civilization when evidence for the proportional exploitation of individual plant and animal species in a range of different regions is more widely available.

The impact of climate change on the populations of the Indus Civilization more broadly will inevitably also reflect the level and nature of interaction between the populations living in different regions. Looking at a global scale, it is clear that the patterns of impact and response to climate change were extremely variable (McAnany and Yoffee 2009; Miller, Moore, and Ryan 2011), and we should expect the same from Indus populations. Humans are unlikely to have been passive in the face of environmental change, and cities and civilizations did not simply disappear. Rather, populations adapt, adjust, move, die out, or thrive, depending on their circumstances.

In the Indus context, we know that the final phase of the urban period (the late Mature Harappan/Harappa 3C phase; ca. 2200–1900 BC) appears to be a phase of intensive interaction, at least in terms of networks of raw material acquisition and redistribution (Law 2011). It is also apparently the period in which Harappa was most densely occupied (Kenoyer 1991: 57; 2005). It was, however, a period of transformation, such that by ca. 1900 BC, a very different socioeconomic and po-



litical structure is evident. On the basis of current data, it appears that in Sindh, the city at Mohenjo-daro was significantly depopulated during the final urban phase and there was a reduction in the intensity of settlement in the region generally (e.g., Joshi, Bala, and Ram 1984; Possehl 2002:212, 241, table 13.2). By ca. 1900 BC in Cholistan, the largest settlements were abandoned or reduced in size and almost all others were displaced (Mughal 1997:51–52), while in Punjab, major settlements, including Harappa, reduced in size (Kenoyer 2005, 2008; Wright 2010:310). Analysis of pathologies visible on skeletons from Cemeteries R37 and H at Harappa, which span this protracted period of transition, has revealed evidence for various infections and diseases, including leprosy and tuberculosis, which indicate deteriorating health (Robbins Schug and Blevins 2016; Robbins Schug et al. 2013a, 2013b). The response in Haryana and Gujarat is visible in the abandonment of large settlements and a focus on smaller town or village-sized settlements.

The review presented here highlights internal dynamics and frames them in relation to a changing climatic context, but we also know that other cultural dynamics were also at play within the Indus zone and the surrounding regions. These include the deterioration of trade through the Persian Gulf, the increased evidence for contact with the populations of inner Asia (e.g., Bactria Margiana Archaeological Complex, or BMAC), and the establishment of new settlements in borderland areas whose inhabitants used distinctive material culture (e.g., Pirak, Jarrige, and Santoni 1979; see Wright 2010:228–230, 308–325).

Precisely how all of these developments interrelate and, in turn, articulate with a weakening of the summer monsoon is as yet unclear, but it is possible that climate change introduced a degree of entropy into a very complex and interactive urbanized system, potentially creating unpredictable unpredictability. Large cities and high local population densities may have become unsustainable, but sustainability, resilience, and continuity may have been possible by embracing rural lifeways that saw the maintenance and dispersal of diverse approaches to subsistence. The need to respond to climate change is only one factor that might have influenced Indus cultural transformation and the adaptation of Indus subsistence practices to a range of ecological zones, and the resilience of these adaptations in the face of climatic and social change remain critical topics for future research.

## Acknowledgments

The collaborative *Land, Water and Settlement* project laid the platform for the *TwoRains* project. The *Land, Water and Settlement* project was primarily funded by a Standard Award from the UK India Education and Research Initiative (UKIERI) under the title “From the Collapse of Harappan Urbanism to the Rise of the Great Early Historic Cities: Investigating the Cultural and Geographical Transformation of Northwest India between 2000 and 300 BC.” Smaller grants were also awarded by the British Academy’s Stein Arnold Fund, the Isaac Newton Trust,

the McDonald Institute for Archaeological Research, and the Natural Environment Research Council. The PhD research of Sayantani Neogi was funded by UKIERI, and that of Jennifer Bates was funded by the Arts and Humanities Research Council. This paper was finalized as part of the *TwoRains* project, which was funded by the European Research Council under the European Union’s Horizon 2020 research and innovation programme (grant agreement 648609). We would like to thank a large number of individuals and institutions that have made this project possible. First, we thank A. Vaish, K. N. Srivastava, and Dr. G. S. Gupta (Director General, Archaeological Survey of India [ASI]), Dr. B. R. Mani (Additional Director General, ASI), and Dr. R. S. Fonia and Dr. S. P. Manik (Directors of Excavations and Explorations, ASI) for granting us permission to carry out the field research. The collaborative agreement on which this project is based was signed by Prof. P. Singh, Vice Chancellor of Banaras Hindu University (BHU), and Dr. K. Pretty, Pro-Vice Chancellor of the University of Cambridge. We are also grateful to the current Vice Chancellors of BHU, Prof. D. P. Singh and Dr. L. Singh. We have been given abundant support by Prof. S. R. Dubey, former head of the Department of Ancient Indian History, Culture and Archaeology, BHU, and Prof. G. Barker, former head of the Division of Archaeology, University of Cambridge and Director of the McDonald Institute of Archaeological Research. We would also like to acknowledge the assistance, advice and hospitality of Prof. A. Singh (Rohtak University), Dr. N. Ahuja (Jawaharlal Nehru University), Prof. M. K. Jones (Cambridge), J. R. Knox (formerly of the British Museum), and, particularly, Dr. R. Tewari (Director General, ASI, former head of Uttar Pradesh State Archaeology), Dr. K. S. Saraswat (formerly of the Birbal Sahni Institute), and Dr. P. Joglekar (Deccan College, Pune), all of whom joined us in the field. We would also like to offer grateful thanks to Profs. R. Meadow, K. Thomas, and R. Wright and to Dr. E. Cork for reading early drafts of this paper and offering a range of helpful suggestions, correctives, and safety ropes that helped us keep focused. We would also like to thank Prof. M. Madella, who has been a constant source of advice and direct support in several instances. Last, we would also like to thank the three anonymous reviewers who provided useful comments and criticisms. These readers may not completely agree with the opinions expressed in the final paper, but their comments have hopefully made our arguments more robust and helped us make this a better and more rounded work.

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## Comments

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Petrie et al.’s article, at first glance, appears to be related to climatic change and understanding subsistence and settlement

variation within a small region of the Indus Valley Civilization. However, the authors conduct a vast synthesis concerning subsistence (primarily agriculture) variation, material culture, settlement pattern, and hydrological regimes during the third millennium BC. The key focus for this study is diversity and understanding how ancient peoples focused on adapting to a highly diverse and fluctuating environment, both in the short term of generations and the longer term of almost a thousand years of occupation in the region. The synthetic nature of this article is hinted at in relation to the project title, *Land, Water and Settlement* project; the research focus of this project now continues with the interdisciplinary work of the *TwoRains* project.

While climate studies related to ancient societies have been an important part of archaeological research, these studies have gained additional importance and a greater visibility within the field due to the political and social significance of understanding current and past climate change. Within the past 5 years, several studies have focused on the role of climate change and the decline of the Indus Valley Tradition (i.e., Giosan et al. 2012). This research looks at very large-scale global monsoonal models and applies these to a large, regional context such as the Indus Valley Civilization. While I disagree with some of the conclusions and applications of these large, global models, these studies have brought into the forefront the need for more regional research.

One of the most powerful aspects of this paper is its recognition of the amount of regional variation that exists in terms of rainfall patterns, hydrological patterns, and monsoonal cycles across the area that encompasses the almost 1 million sq. km that is thought to represent the expanse of the Indus Valley Civilization. The authors' review of the amount of diversity in terms of settlement, material culture, and agricultural practices that exist across this landscape is key to our understanding these flexible socioecological adaptations. However, only a few sites possess the detailed information that allow for ecological and subsistence reconstruction. While most researchers recognize that there is diversity across this larger landscape, there is still the pervading myth of cultural homogeneity within the Indus Valley Civilization. By recognizing the more regional aspect of various characteristics of the Indus Valley Civilization, the authors are able to address a much richer landscape of socioecological adaptation, albeit for the specific region of Haryana/northern Punjab area.

This multidisciplinary project focuses on creating a localized model for the Haryana/northern Punjab region using geological, geomorphological, and archaeological data. By using specific regional data, the authors are filling out a detailed understanding of the environment for a specific region. This should set the stage and create a model for ecological research for future directions. This study allows us to understand the regional climatic changes that occurred in this area. However, Petrie et al. warn us not to extrapolate these data to the Indus region overall.

During the summary of data related to diverse hydrological patterns, there are two important points that should be em-

phasized here: the hydrology Ghaggar-Hakra River and the settlement pattern contemporaneity. Petrie and colleagues present data that suggest the Ghaggar-Hakra River was not a perennial source of water. Additionally, the density of settlements along the area, at least in terms of the Cholistan region in Pakistan, were probably not all occupied at the same time; in fact, Petrie et al. suggest that as few as 5%–10% of the settlements were contemporaneous. These two data sets suggest that many aspects of current presentations related to the role of this river system to the Indus Valley Civilizations are overly simplistic.

This article is data heavy and deserves a second or third reading to understand the implications of the research. Recognition of the diversity of the ecological and hydrological setting is the first step in beginning to understand the flexible adaptations that many of the regional aspects of the Indus Valley Civilization must have had. Petrie et al. state that some populations within this large regional civilization were well adapted to ecological change as reflected in subsistence strategies and water management, and thus we may need to rethink our understanding of what it means for this civilization's "end."

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This paper makes a substantial contribution to the literature on complex societies and environmental effects, using the Indus Civilization case. The authors present both their own important new data and an invaluable summary of similar collaborative projects from elsewhere in the Indus world. They place these and other recent climatic studies in environmental and cultural context, employing approaches from both the sciences and the humanities. Indus researchers, those looking to use the Indus as a comparative case, and scholars interested in the relationship between environment and society broadly will all find this paper of great use, especially as Petrie et al. have employed a clear, direct writing style.

Readers now expect the "but" explaining where I think this research went wrong. It is not coming. It is encouraging to see this presentation in a high-profile anthropology journal of the excellent work done by Indus scholars on the environment and climate change over the past few decades (and more). It is even better to see a publication emphasizing the importance of considering human adaptability and traditions when assessing the possible role of climatic change in social and cultural change, contributing this important anthropological perspective to current debates in several of the highest-profile general science journals.

I am particularly thankful to see that the authors stress the dual-rainfall nature of Indus climatic regimes, as well as the multiplicity of environmental contexts found within the borders of this expansive ancient society. Too many studies of ancient climate change for this region focus solely on changes

in the monsoon summer rainfall system and ignore the winter rainfall regime. There is no question that the monsoon system is and was critical for this entire region, and especially so for the eastern areas within modern-day India, both for direct rainfall and for runoff or collected water supply. The winter rainfall regime seems to have also been critical for Indus agricultural systems, though, at the least for western Indus regions and the greater Indus River floodplains in Punjab and Sindh, and we lose a great part of the potential flexibility and adaptability of ancient (and modern) agricultural systems if we do not consider both systems, as the authors emphasize.

The authors highlight the importance of examining local conditions as well as large-scale ones; through this, they provide pathways from such large-scale climate reconstructions to an understanding of the role of human actions and reactions. For example, looking at the local sources and methods of agricultural water supply shows the complexity of water availability for Indus farmers, beyond a simple rainfall-based climate change model, as the authors note. Their discussion of the paleo-Ghaggar/Hakra hydraulic regime is a useful update, and I look forward to the forthcoming publication on the associated settlement patterns, particularly if they prove to be as significant as the reassessment of the patterns in northwest India (Singh et al. 2010b, 2011).

There is a common but significant oversight here, found in most discussions of the effects of climatic/environmental change on the history of the Indus Civilization as a tradition and as a complex society: the tendency to look at only agricultural crops, more specifically only at plant foods, ignoring the effects on animal and other plant production systems. (I am also guilty of this in the writings the authors cite, except for the weaselly insertion of a line or a footnote indicating that animal food production is important but that I will not deal with it.) Since the early days of Indus archaeology and especially since the first environmentally inclusive archaeological projects of the 1970s and '80s, researchers have noted that animal husbandry was a major part of Indus food production systems. Mixed agricultural economies were certainly an important part of Indus food production, with crop farmers also keeping animals, perhaps in significant numbers, as part of the well-known mixed economy benefits of animal and crop co-production. But there must also have been pastoral communities at this time, communities more focused on animals than plants (e.g., Bhan 2011; Mallah 2011; Meadow 1996; Meadow and Patel 2003; Mughal 1997:59). Such communities could have followed a range of lifestyles, from seminomadic to primarily settled, including the opportunistic growing of fodder. What would be the effects of climate change on such animal-oriented communities? Were they even more dependent than farmers on rainfall for food production? What other strategies might they have had to deal with the “predictable unpredictability” of water and, therefore, fodder supply in these regions? Aside from Reddy (1997, 2003) and Chase and colleagues (Chase 2014; Chase et al. 2014) for Gujarat and Thomas (2003) for Bannu in the far northwest, few Indus researchers have modeled how such communities might have managed to feed

their animals and how this relationship between plant and animal food production systems might have changed through time, although this may be part of the work of the North Gujarat Archaeological Project (Madella et al. 2010) or other projects noted by Petrie et al. Similarly, fish and other wild plant and animal foods would also be affected by climatic/environmental conditions; we know that fish were important for at least some Indus communities (Belcher 1998, 2003). Nonfood plant and animal products were likely critical aspects of Indus economic systems, particularly for fiber and cloth production, and climate-linked upsets in these production systems could have had devastating effects on exchange networks or tax/tribute systems required to sustain Indus social and political structures.

As always, there is still plenty of work to be done. This does not take away from the substantial contribution made by the researchers of the *Land, Water and Settlement* project and the other projects discussed in this paper. Their example here of how to assess the effects of climate change on plant-based agricultural systems, including an examination of existing methods of adaptation and resiliency already practiced in the Indus tradition, have laid the groundwork for approaches that can be applied to all of the other production systems described above. The authors are to be highly commended on the result.

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First, the authors are to be commended for taking existing models regarding the unique nature of the diversity of Indus Civilization environment and building a more concrete understanding of the influence climate change had on agricultural practices and, subsequently, the evolution of this civilization. These are important issues where more data and more thorough discussions are needed. The paper's strength lies in its addition of new data (mainly from Haryana) and its synthesis of existing arguments regarding agricultural diversity and the significance of climate change, especially as it relates to local environments. While these contributions are very valuable, the paper at times fails to adequately distinguish between which ideas are completely new and novel and which arguments are, in essence, extensions of existing debates. I strongly disagree with their conclusion that “robust evidence to support” the existence of ecocultural or agroecological domains is not available. The importance of understanding the diverse and varied ecologies of this civilization has been an accepted reality for some time as is the argument that the “proportional exploitation of winter and summer crops” may have made it possible for populations in some areas to adjust to climate change. The contention that the cultural and environmental variation across the Indus zone is underappreciated, especially when it comes to explaining the decline of the urban



centers, is puzzling, as this is well recognized in the archaeological record. The argument that to understand cropping at any point in time in South Asia, due to its great regional environmental diversity, a local ecological approach was the soundest was among the several ideas incorporated into Osada Toshiki's project Environmental Change and the Indus Civilization. This major project, supported by the Research Institute for Humanity and Nature (RIHN; 2004–2011), drew several similar conclusions to those that appear here in this paper and in other papers associated with the *Land, Water and Settlement* project. For example, the RIHN project discussed how climatic stress was experienced in different regions of the Indus Civilization in different ways; in some areas, the effects were much more extreme and made it difficult to produce the crops necessary to keep several large urban centers sustainable. One conclusion was that the civilization's communities that were based on diverse multiseasonal cropping (including both summer and winter crops) with local processing and storage (often at the household level) were more adaptive to climate stress.

One minor concern I have with this paper is the extensive use or reference to forthcoming publications. This came up more than 15 times in the paper, and while I appreciate the difficulty in the pace in which material gets published, it means that the reader has to take the authors' word for much of the new information without being able to judge its quality oneself.

Finally, I am excited to see the authors' efforts at constructing a quantifiable and comparable archaeobotanical database. This type of approach, until recently, has been relatively rare for the Indus Civilization, although the need for such an approach is well understood and has slowly become accepted as the best approach (see Fuller and Weber 2006). Surprisingly, the article either misunderstands the results or challenges the value of the archaeobotanical data collected from Rojdi, Farmana, and Harappa. Summer crops were not only clearly evident at all three sites but were an important part of the agricultural strategy. Rojdi was one of the first large quantifiable archaeobotanical data sets collected in South Asia (Weber 1991). Evidence from the analysis of more than 14,000 seeds showed that summer crops remained prominent even after the decline of the monsoons. At Farmana, phytoliths, starches, and carbonized seeds were recovered and analyzed (Weber, Kashyap, and Mounce 2011), and some of this material was individually dated to secure its age. The material shows that while both summer and winter crops were in use throughout its occupation, the ubiquity and density of summer crops remained constant, while the winter crops declined during the Late Period. Published data and recently completed analysis indicate that summer crops were always important even during the mature occupation where they accounted for nearly 35% of the crops. Summer crop production never declined even with a decline in the monsoons.

The most interesting archaeobotanical data set, as well as the largest from any Indus site, is from the city of Harappa.

Seeds have been individually dated from systematically collected samples, and presently more than 200,000 seeds have been analyzed. The database is completely quantifiable. Such a large number of seeds have taken many years to analyze, but the goal is to have the complete collection published and available by 2018. While the various occupations at Harappa (3300–1700 BC) show winter cropping as the most important, summer crops were being used throughout. During Period 3A (2600–2400 BC) and again in Periods 4/5 (1900–1700), summer crops increased in use according to measures of ubiquity, density, and frequency. Based on this data, I have argued that communities like Harappa made themselves sustainable during periods of climatic stress because they were capable of harvesting both summer and winter crops. Unlike other large Indus cities, Harappa was not abandoned in spite of indications of stress and decline.

In sum, we know a lot more about cropping and shifts in agricultural practices and adaptive abilities in different regions of the Indus Civilization than this paper acknowledges. Regional cropping variability due to ecological variation has been going on for a long time in South Asia and continues today. Climatic shifts need to be understood at the local level if we are to better comprehend the evolution of the Indus Civilization. It is only from sites where we have extensive horizontal exposures, with samples representing many distinct features such as floors, storage bins, trash areas, streets, drains, burials, and so on that we can begin to appreciate the relationship of plants to the rest of the material record and thus to cultural variability. Notwithstanding my caveats, the debate raised in this paper concerning climate change, diverse ecologies, and adaptability in the Indus Civilization is very welcome.

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Petrie and his colleagues make an argument for the significance of climate change and diverse ecologies as factors in adaptability and resilience in the Indus Civilization. They also review the current results of their *Land, Water and Settlement* research that will fill in important gaps. While the authors appear to agree that cropping patterns and water systems influenced the growth and decline of the Indus Civilization, in spite of what they consider the poor quality of the current evidence, they fail to consider the diverse social organization that enabled regionally distinct communities to adapt differently when confronted with regional and global shifts in moisture systems.

True enough, we learn a lot about subsistence practices and ecological variability, but there is more to it than available foods and climate. Cropping, processing, and management of plants and water directly and indirectly reflect social processes and social organization. As examples of the ways in which they

influence adaptability and resilience, I turn to good contextual data for cropping patterns at Rojdi and Harappa and water management systems at Dholavira.

### Cropping Patterns, Diverse Ecologies, and Household Economies

Rojdi, a 12-ha agricultural community in Gujarat, and Harappa, a major center in the late and posturban phases of the Indus, provide contrasting adjustments to climate change. These results are based on excavated and stratified levels collected from primary, secondary, and tertiary contexts, some of which are accelerator mass spectrometry dated. Of specific relevance is the evidence for chaff and weed remains at both sites. Residues of chaff and weeds are indicative of the threshing, winnowing, grinding, and cleaning of grains (Weber 1996, 1999) in households. At Harappa, they are present only in the latest phases of occupation, when the average area of the site diminished. During the urban phases, the city's agricultural production was based on large-scale, seasonally based cultivation in which the processing of crops took place in fields (Weber 1999, 2003:181) and is suggestive of a community or centralized organization. In distinction, the presence of chaff and weeds in households reflects a political and social reorganization that may have resulted from ecological stress due to climate changes. This pattern differed from the long-term settlement at Rojdi. Millet was a preferred crop, and this small-seeded and lower-yielding grain was well adapted to a farming community with a lower population than Harappa (Weber 2007, 2010). Although there were some changes in cropping patterns at Rojdi, the presence of chaff and weeds is consistent with household production. Both Harappa and Rojdi continued to be occupied after the critical 1900 BCE date invoked by Petrie and his colleagues. When the two settlements are compared, their ability to adapt to climate change differed. At Harappa, it was based on a shift from a complex social organization based on a centralized or communal agricultural system and a more sustainable and less complex social organization that was based in households. Unlike the major center at Mohenjo-daro, for example, Harappa continued to be occupied at least until 1700 BCE (Wright 2010). At Rojdi and neighboring settlements, farmers continued to be based on household production and the cultivation of millets until at least 1700 BCE and possibly later (Weber 1998, 2007; Weber, Barela, and Lehman 2010).

### Water Management

The water source at Dholavira does not conform to the elaborate systems envisioned by a model focused on irrigation. Rainfall at Dholavira is exceedingly low, and the landscape is absent of a major river system.<sup>1</sup> Better monsoon conditions

1. In a widely circulated video production of the archaeology at Dholavira, a narrator speaks of a river system. In publications, Bisht is explicit that the water drained off of a "runnel."

existed at 3000 BCE, when the first settlers came to the region, but even then precipitation was marginal (Agrawal 2009). In spite of the challenges of low rainfall and a harsh environment, the city became one of the Indus's major centers.

The first settlers at Dholavira built a modest water system in which they channeled the flow of an ancient runnel to provide potable water and what appears to be a still-water system (Scarborough 1993, 2003; Scarborough and Lucero 2010). Its construction at Dholavira is documented from the initial (preurban) period when it was cut into base rock for the storage of potable water. Very likely, a small group of knowledgeable farmers built and managed the timing and maintenance of the flow of water. Later in the urban period, rock-cut reservoirs and dams were constructed from nonlocal stones that were procured from a distance, when the system was expanded, perhaps due to a population influx and expansion of the city. The new system was massive. Many more reservoirs and dams were constructed that provided water for a variety of human needs, including drinking water at its highest reaches. As water cascaded through the terraced city of approximately 100 ha, it reached the lower levels of the city carrying potable and domestic water before being channeled to agricultural fields (Bisht 1994, 2005, 2009). The complexity of this system and the substantial labor force needed to construct and manage its flow could have been managed and monitored at each level by collective groups, as has been documented elsewhere by a more centralized bureaucracy in view of its complexity. The Dholavira data provide evidence for the significance of water storage and the contribution of small-scale producers at Indus's major centers.

Though Dholavira's reservoir system did break down, we know from my discussion of Rojdi that populations remained at sustainable levels in interior settlements after Dholavira was no longer inhabited. It was the dual presence of these very different agricultural strategies and the small-scale household production that contributed to the sustainability of settlement in Gujarat. As Weber and others have noted, these changes may be part of wider social process elsewhere (Fuller and Stevens 2012; Weber 1999, 2003). I look forward to the published results of the *Land, Water and Settlement* research and whether their results are consistent with ones documented at Dholavira, Rojdi, and Harappa.

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## Reply

We would like to thank our four colleagues for their comments, which in general are complimentary but also raise specific issues and/or points of criticism. As Miller recognizes, our paper sets out to speak to a broad audience. We set out to synthesize a range of evidence from the Indus case in a way that hopefully allows us to emphasize how it speaks to themes relevant to non-Indus as well as Indus scholars in both the

sciences and humanities. We also stand by our aim to propel the Indus example into broader debates, particularly those related to adaptation and resilience.

All of the reviewers commend us for building on existing models of Indus environmental diversity to achieve a more concrete understanding of the influence climate change had on its agricultural practices and evolution. However, Weber, and to some degree Wright, suggest that we do not appropriately acknowledge previous scholarship, particularly that documenting agricultural and environmental diversity in the Indus context. We disagree with this and a number of associated suggestions.

Throughout our paper, we acknowledge that previous work has addressed related themes and cite as much of this research as is feasible, and we note Miller's recognition that we highlight the range of "excellent work done by Indus scholars on the environment and climate." However, we also make clear that there are important differences between our approach and results and those of previous work, both in terms of theoretical framework and the empirical approach of investigating one specific region in detail.

This leads us to respond to Weber's particular claim that Toshiki Osada's Environmental Change and the Indus Civilization project based at Research Institute for Humanity and Nature (RIHN) drew several similar conclusions to those made by the *Land, Water and Settlement* project, especially as he refrains from citing any supporting references. Osada and colleagues have published a formidable array of papers and edited volumes on their work, and there is no question that the RIHN project has been extremely important for Indus archaeology in its investigation of sites in multiple regions. In many ways, the team's key contribution has come via its collaborative excavations at settlement sites, including Girawad, Farmana, Madina, and Kanmer, and impressively, final publications of these excavations were available within 3 years of the completion of the fieldwork. It should, however, be acknowledged that, to date, there has been no synthetic presentation of its results, and the project's discussion of environmental factors relevant to these sites is either preliminary or limited (e.g., Lancelotti and Madella 2010; Pokharia 2012; Rajagur and Deo 2008; Weber, Kashyap, and Mounce 2011). Further, the broader project outputs on climate and environmental change have either not been proximate (lake data from Nepal; Nakamura et al. 2016) or, in our opinion, adequately resolved (e.g., a relatively limited number of optically stimulated luminescence dates relating to river-shift investigations; Maemoku et al. 2012; Shitaoka, Maemoku, and Nagatomo 2012). We argue that far more proximate and nuanced analyses are required to provide a well-grounded palaeoclimatic framework for the Indus region as a whole, and more comprehensive analyses are required to resolve important questions about fluvial regimes.

The *Land, Water and Settlement* project has obtained proximate palaeoclimate data from Kotla Dahar (Dixit, Hodell, and Petrie 2014) and two other locations across northwest India (Dixit et al. 2014, 2015), and these records attest to consider-

able climatic variation in the eastern Indus region during the Holocene. We have also mapped modern climatic patterns in relation to Indus settlement distribution (fig. 2A, 2B), and our archaeological and archaeobotanical investigations at six separate settlement sites across this one region highlight the likelihood that there was considerable variation in ecological and human adaptation and response within this region in the past (Bates 2016; Petrie and Bates, forthcoming). In this regard, we note that both Belcher and Miller highlight the significance of the local nature and amount of regional variation that we discuss. We thus emphasize that our work has different objectives and outcomes to the RIHN project, and our conclusions about adaptation and resilience are both novel and robustly integrated.

We certainly do not suggest that there are no robust data on archaeobotanical or palaeoenvironmental change available, nor do we suggest that cultural and environmental variation across the Indus zone has not been recognized in the archaeological record. We do, however, highlight that some of the available data sets are either partial or incompletely published. We argue that the overall corpus of environmental evidence from the Indus zone that is published, including information about proportions of summer/winter cropping, is not yet detailed enough to constitute a robust basis for building appropriately nuanced models of agroecological diversity or to test their veracity. We also stress that there is likely to be considerably more variation than is currently recognized.

Leaving aside our work, well-resolved archaeobotanical information is typically available from one or a small number of archaeological sites in any one area across the Indus zone. The important data from Rojdi (Weber 1991, 1999), Babar Kot and Oriyo Timbo (Reddy 1997, 2003), and Harappa (e.g., Weber 1999, 2003) can tell us only so much about Gujarat and Punjab, respectively, as both are ecologically and hydrologically diverse regions. Such limitations make consideration of the impact of climate change even more challenging. Thus, while Wright (2010) and others have addressed the implications of climatic and agricultural variation for processes of deurbanization, we argue that we still lack enough fundamental data to ground those ideas and test the theories, and these limitations should be acknowledged.

In our view, the *Land, Water and Settlement* project presents an important contrast in approach, which has enabled us to demonstrate that northwest India in the Indus period is far more environmentally, agriculturally, and culturally diverse than has ever been previously acknowledged. We argue that this level of intraregional diversity has ramifications for our understanding of the Indus zone as a whole—as well as the extent to which the available data permit adequate modeling of socioecological systems, cultural diversity, and responses to climate change.

In a similar vein, we suggest that, overall, the Indus archaeobotanical evidence base remains as yet insufficient to resolve important patterns of social and economic organization. We concur with Wright's assertion that archaeobotanical analysis offers extremely important insights into these issues, and she



rightly points out the importance of evidence of chaff and weeds for gaining insight into agricultural labor organization and the agricultural economy. With respect to information about local conditions and their relationship to agricultural cropping and associated weeds, Weber's (1992, 1999) detailed and comprehensive work at Rojdi and Reddy's (1997, 2003) work at Babar Kot and Oriyo Timbo are exemplary and are published with raw data, facilitating detailed (re)analysis by others. However, the work at these and the *Land, Water and Settlement* sites are the exception rather than the norm. As Weber notes, the full assemblage from Harappa—without doubt, the most important Indus archaeobotanical assemblage from an urban site to date—is still under analysis. This includes the crop-processing and weed-ecology data that are essential for discussions of both the ecology and social organization of agricultural production. We firmly believe that when complete, the analysis of the full archaeobotanical data set from Harappa will revolutionize our understanding of many aspects of social and economic life at this major city and its hinterland and potentially force further reconsideration of the aspects of adaptation and resilience explored here. If we are to properly characterize agroecological diversity, far more data needs to be collated for each area, including consideration of local-scale soil and weed ecology, and we believe that the *Land, Water and Settlement* project has made considerable strides in this regard in northwest India (e.g., Bates 2016; Neogi 2013; Petrie and Bates, forthcoming).

We also fully concur with Wright's point that there is more to understanding the Indus than available foods and climate. While our focus is on the relationships between environment and Indus society, we do emphasize the importance of recognizing human agency, human choice, and social processes in how Indus populations responded to diverse and changing environments. We also agree with Wright's point that diverse social organization may have supported or shaped human adaptation to climatic shifts and discuss this in our reassessment of settlement patterns in Cholistan and through our evidence for cultural diversity in settlement location and the use of ceramic vessels in northwest India.

Wright makes another important point about the diverse nature of water management across the Indus zone, and this sits well with our view that water management is fundamental to understanding how Indus populations responded to a variable and changing climate. The range of approaches to water management practised within northwest India are fully in keeping with Wright's points about the diversity of water management evident at Rojdi and Dholavira in Gujarat. We do reiterate, however, that there is a clear need to carry out further research into Indus water management practices as part of efforts to understand how Indus societies responded to varied and changing environments across the diverse setting that they occupied.

As Miller notes, many of the studies exploring ancient climate change consider proxies relevant to the summer rainfall system but overlook the dynamics of the winter rainfall regime. H. M.-L. Miller (2006, 2015) has previously emphasized the important role of summer rains for winter cropping but

also the critical role of the ancient winter rainfall regime, and her point about the need for information on this weather system is well made. Clarity in this regard will come only from palaeoclimate data sets obtained from Pakistani and Indian Punjab, which must be an objective for future research.

Miller also rightly draws attention to the impact of climate change on nonfood crops, animal husbandry, and pastoral communities. Reduced availability of water is likely to have affected the growing of fiber and oil products, including linseed/flax, mustard, and sesame, particularly as cotton and flax are both thirsty crops. Further attention to both the role of nonfood crops in Indus economies—and how they may have been affected by environmental changes—is another clear avenue for future research, as Miller suggests. The *Land, Water and Settlement* project has considered animal exploitation, but this research is still ongoing and incorporates a spectrum of archaeozoological and isotopic analyses, including analysis of carbon, oxygen, and strontium in tooth enamel carbonate to investigate animal diet and mobility. This research will complement the work on pastoralism mentioned by Miller and contribute to an expansion of knowledge about Indus animal economies, facilitating their integration into discussions of agroecological and economic diversity, adaptation, and resilience.

Weber neatly encapsulates our core contention by reiterating that environment and climate need to be understood at the local level if we are to better comprehend the evolution of the Indus Civilization. Bottom-up approaches that focus on local-scale data relevant for understanding climate and environment are seeing increasing archaeological application, and the need for such evidence to support modeling of human responses to climate change is a key point of our paper. More detailed, multiproxy studies across more parts of the greater Indus zone are needed if we are to reach the stage of being able to compare and contrast responses across different social and ecological Indus settings. Our excavations in northwest India have thus far been limited, but we have excellent stratigraphic and chronological control, and our operations have been widespread in terms of geographical scale. Our work thus creates an opportunity to start understanding variation across an individual region. However, as Miller rightly notes, "there is still plenty of work to be done," and we suggest that further research will increase emphasis on the nature of ecological diversity and human responses to that diversity within each of the large-scale domains, or ecocultural regions, within the greater Indus region. We look forward to being part of that ongoing process through the *TwoRains* project.

—Cameron A. Petrie, Ravindra N. Singh, Jennifer Bates, Yama Dixit, Charly A. I. French, David A. Hodell, Penelope J. Jones, Carla Lancelotti, Frank Lynam, Sayantani Neogi, Arun K. Pandey, Danika Parikh, Vikas Pawar, David I. Redhouse, and Dheerendra P. Singh

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