Investigating adaptation to climate change in the archaeological record: a conceptual framework and an isotopic approach in the Indus Civilisation

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Abstract

Identifying adaptation to climate change in the archaeological record is an important but challenging task. In this paper, we outline a conceptual framework for testing for evidence of climate adaptation by past societies on an explicit empirical basis. This framework is grounded in the concepts of vulnerability, exposure, sensitivity and adaptive capacity, derived from the literature on the likely impacts of future climate change on modern societies. Using these concepts, we propose a model for explicitly testing for adaptation to past climatic shifts on a local, site-specific basis. After describing this model, we outline how we are applying this in an attempt to test for climate adaptation in the context of the Indus Civilisation. Using stable carbon isotope analysis of crop remains, in this ongoing study we are testing for evidence that populations at several Indus settlements, including those detailed in this paper–Harappa, Dabli-vas-Chugta and Masudpur VII–adapted to the likely impacts of weakening monsoon rains c.2200-2000 BC on agricultural water supply. Here, we predict the likely impacts of this climate event on water supply at each site in the *absence* of adaptive response. Using our isotopic results, we will test these predictions and hence establish whether the evidence supports (possibly differential) adaptation.

Introduction

In the context of a modern world in which the risks of climate change are growing ever more apparent, understanding how climate change affected past societies is fast transforming from an academic fascination into an imperative concern. Past populations faced environmental changes of various scales, tempos and degrees, and comprehending how they were affected–and how they coped–has the potential to offer a set of insights that will help us understand, predict and plan for the changes ahead (Mitchell 2008).

In order to realise the potential to draw meaningful insights from the past, however, we need to move beyond dichotomous visions of climatic change as either as a deterministic driver of social transformation, or as an insignificant or irrelevant force. There are, unquestionably, many instances of climatic change in the past of a severity and duration that are likely to have posed significant challenges for contemporary populations (Cronin 2010). However, populations are unlikely to have been passive in the face of these changes. Rather, people would have responded, in various ways and with various degrees of success, depending on both the stresses they faced and the choices available to them within their social, economic and ecological context (Orlove 2005; Brooks 2006;

Van de Noort 2011). It is only by studying these patterns of response–or adaptation–that we can gain a perspective that both enriches our understanding of the past and offers a useful platform for the present.

Investigating adaptation to climate change in the archaeological record does, however, present significant challenges. First and foremost, these are issues of obtaining and integrating a suitable evidence base. This is because demonstrating adaptation to climate change requires multiple strands of evidence, and if we are actually to comprehend the variability and nuances of human decision making on the ground, this evidence must be of a sufficient spatial and temporal resolution to map the local variability in environmental and social conditions that may have been relevant to those decision making processes. Overall, the necessary lines of evidence include:

1. Evidence of climatic impact, from a palaeoclimatic record capable of providing a precise enough delineation of local environmental change to contextualise human decisions.
2. Evidence of a social process that could be reasonably interpreted as an adaptive response to that climatic impact.
3. Most critically of all, evidence of a causal link between the impact and adaptive response.

Further, if we are to extend this to try to measure the success (or failure) of any adaptive response, we also need a means of testing the degree to which the response changed the degree of climatic impact suffered. Given the limitations of the palaeoecological and archaeological record, fulfilling these requirements is a non-trivial task. Consequently, few studies have successfully generated firm empirical evidence for the presence, absence, nature and/or degree of adaptation to climate change, either in South Asia or elsewhere.

In this paper, we outline a framework for explicitly testing adaptation to climate change on a site-specific basis. We argue that taking such a local-scale approach is necessary because there is likely to be significant local-scale variability in the factors that determine the degree of climatic impact suffered, as well as the range of adaptive responses available to a given population. Without an appreciation of this variability in the factors that influence behaviour, we cannot hope to understand patterns of past environmental impact and human response.

Our framework for testing adaptation to climate change consists of three steps:

1. Predict the degree to which a given climatic change is likely to have affected the community within a settlement, assuming the absence of any adaptive response.
2. Test these predictions empirically.
3. Evaluate the difference between the predicted and measured impacts. We argue that this provides a means of assessing the extent of any adaptive response–that is, how much it was able to buffer or mitigate any climatic impacts.

Here, we demonstrate how we are applying this framework to test for evidence of climate adaptation at several Indus Civilisation settlements, using stable carbon isotope analysis of crop remains. The Indus is a context in which our approach is particularly valuable: the region's high degree of climatic and ecological variability demands this type of local-scale analysis, and the long history of debate about the impacts of climate change on the Indus Civilisation (e.g. Madella and Fuller 2006; MacDonald 2011) creates a context in which testing for climate adaptation has particular archaeological relevance. The overall framework is, however, highly flexible: it could be applied to any location on any time-scale, and does not require the climatic impacts or adaptive response to be measured using any particular proxy or technique. In this paper, we first explain the basis for this overall conceptual model, before introducing carbon isotope analysis as one means of implementing this model; and finally outlining its application in the Indus Civilisation.

The overall conceptual framework: predict sensitivity and test impact

The concepts of vulnerability, exposure, sensitivity and adaptive capacity that underlie our approach are derived from the literature predicting the impacts of current and future climate change on modern societies. These concepts are grounded in an earth-systems paradigm, which views human settlements as part of a complex, dynamic system of interacting human and ecological processes (Folke 2006; Lorenz 2010; An and López-Carr 2012).

Each of the concepts listed above has been defined in numerous ways. However, most accepted definitions of vulnerability centre broadly on the idea of susceptibility to harm, and more formally as the potential for change or transformation when a socio-ecological system is subjected to a climatic perturbation (Folke 2006; Gallopín 2006; Smit and Wandel 2006). Here, following Gallopín (2006), we define vulnerability to climate change as the propensity of a socio-ecological system to suffer significant transformations as a consequence of a climatic perturbation. Working from this basis, the vulnerability of any given socio-ecological system can be seen as a function of three discrete factors (Fig. 01):

1. *Exposure*–the degree and/or duration of the climatic perturbation.
2. *Sensitivity*–the susceptibility of the system to damage or harm from a particular degree of exposure.
3. *Adaptive capacity*–the capacity of the system to make adjustments that moderate potential damage, exploit opportunities and/or cope with the consequences of climatic change.

In other words, the degree of harm a socio-ecological system is expected to suffer is a function of a) how big the impact is; b) how much social and/or ecological function is likely to be affected by that impact; and c) the likelihood the society (or broader socio-ecological system) will be able to adapt. While this conceptual model was developed to predict vulnerability in the future, we argue that distinguishing these facets of climatic vulnerability is also useful in discussions of climatic impacts in the past (see for example Widgren 2012; Gronenborn et al. 2014 for similar applications in the context of resilience studies), and use them to form the basis of our framework.

This framework for testing adaptation starts from modelling or estimating the first two components of vulnerability to climate change, exposure and sensitivity. Exposure–the nature and degree of climatic impacts faced–can be estimated by gathering suitable palaeoecological information. Estimating sensitivity is more complex, but in most cases it will be possible to measure many of the most significant factors in the archaeological record–for example, aspects of a settlement's hydrological, ecological and geographical context, and potentially its social and/or ecological connectivity. On this basis, while it may not be possible to understand all of the contributing factors, in most cases it will be possible to make a reasonable prediction of the sensitivity of a settlement, either in absolute or comparative terms.

Estimating the final component of vulnerability, adaptive capacity, is more difficult in an archaeological context. Many of the relevant processes and characteristics, which include effectiveness of governance, adequacy of infrastructure and technological capacity (Brooks et al. 2005; Field et al. 2014) are and may always be archaeologically invisible. As such, it is not appropriate to quantify or compare adaptive capacity in the past; however, we suggest it is nonetheless useful to explicitly acknowledge the importance of these characteristics and potentially incorporate them into hypothesis or model-building exercises.

Building on this theoretical basis, we propose a simple framework to test for climate adaptation in the archaeological record. This consists of the following components:

1. Predict exposure, or the magnitude of climatic impact faced, from the palaeoclimatic record.
2. Predict the sensitivity of the settlement/s in question to this degree of exposure.
3. Combining these two predictions, estimate the actual impact that would be expected to occur at each settlement in the absence of any adaptive response.
4. Empirically test the magnitude of impact that actually occurred.
5. Ascertain whether the degree and/or patterns of impact differ from those expected. If less than expected, this can be considered evidence of an adaptive response. In the context of multiple settlements, patterns of impact that differ from those expected can be considered evidence of differential adaptive response.

Carbon isotope analysis of crop remains as an empirical test

Employing this framework requires an empirical means of testing the combined outcome of

a) the climatic change; and b) any adaptive response. This obliges us to be very specific about the type of climatic impact we are trying to test: how exactly are we proposing that climate change affected this society, and how exactly do we propose that people might have adapted in response? And what mechanism do we have to test these processes?

Here, we focus on impacts on agricultural water supply as one of the principal pathways by which climate change may have affected past societies. Agricultural water supply is vulnerable to shifts in climatic parameters, and a normative model might predict that by undermining agricultural water supply, climate change leads to crop water stress and consequently a reduction in the size and/or reliability of crop yields. This in turn undermines food security, and thereby social and economic stability (Fig.02).

This is certainly a feasible model of how climatic changes could have placed stress on past societies. Indeed, in contexts from the Indus to the Maya, it is one of causal pathways most frequently invoked in arguments relating climate change to social collapse or transformation (Haug et al. 2003; Staubwasser 2003; Orlove 2005; Staubwasser and Weiss 2006; Gill et al. 2007; Prasad et al. 2014).

It is also a model in which considering adaptation is important. Settled populations could potentially have employed a range of strategies to minimise the impacts of climate change on crop water supply, including forms of increased or altered water management. In various contexts, including the Indus, some authors have argued that irrigation or water management was or may have been employed to mitigate the impacts of climate change on agricultural water supply (e.g. Pandey et al. 2003). However, to date these assertions have rarely been supported with a firm empirical evidence base, either in the form of proxy indicators or via 'on ground' evidence such as irrigation structures.

Carbon isotope analysis of crop remains now provides a means of providing such evidence. This technique measures the ratio of two stable forms of carbon, Carbon-12 and Carbon-13, in plant tissues. In plants which use the C_3 photosynthetic pathway (including most major crops), in water-limited environments, this ratio, expressed as $\delta^{13}C$, can be used as a proxy for water stress (Araus et al. 1999; Dawson et al. 2002). This is because the carbon in plant tissues is derived from carbon dioxide (CO_2) fixed into sugars via photosynthesis. Plant tissues are isotopically lighter than atmospheric CO_2, because of isotopic fractionation that occurs during the diffusion of CO_2 into the leaf, and during the enzymatic uptake of CO_2 by the photosynthetic enzyme 'Rubisco'. If water is ample, plants open the stomata (pores) on their leaves, allowing a free flow of carbon dioxide into and out of the leaf, allowing maximum possible discrimination against the heavier isotope, Carbon-13 (Farquhar et al. 1982; Zhang et al. 2009, see also Fig. 03). Under water stress, however, plants usually close their stomata, preventing water loss through evapo-transpiration, but limiting CO_2

diffusion into and out of the leaf. The resultant plant tissues have an accordingly 'heavier' carbon isotopic ratio (Farquhar et al. 1989; Dawson et al. 2002). Although other factors such as nutrient availability, light, altitude, temperature and genotype influence also affect isotopic discrimination, water availability is generally a primary determinant of $\delta^{13}C$ where it is one of the principal constraints on plant growth (Araus et al. 2003). In appropriate environmental contexts and with due consideration of other potential mediating factors, $\delta^{13}C$ can thus be used as a proxy for plant water availability in the past (e.g. Araus et al. 1997; Wallace et al 2013).

Analysing the $\delta^{13}C$ of crop remains excavated from archaeological sites thus offers a direct means of assessing the degree of water stress experienced by the crops used to supply that settlement (Aguilera et al. 2011; Araus et al. 2014; Riehl et al. 2014). In this way, it can be used to test the tangible, practical impact of past climatic changes on agricultural water supply. Within the framework outlined above, we can therefore use $\delta^{13}C$ as a means of testing hypotheses about climate adaptation: we can predict the impact of climate change on crop water stress in both the presence and absence of adaptive responses, and then measure the actual impact using $\delta^{13}C$ of archaeobotanical material as a proxy. This is our aim in an ongoing study of water stress in the Indus Civilisation, which we detail in the following section.

Applying the framework: a case study in the Indus Civilisation

The Indus Civilisation is a context in which the question of adaptation to climate change is highly relevant. Climate change and its impacts have long been a topic of contention and debate in the Indus setting: while some authors have argued there is no clear evidence for a significant shift in rainfall patterns (e.g. Possehl 1997), others posit climate change as a primary driver of the Civilisation's collapse and transformation (e.g. Staubwasser and Weiss 2006; Ponton et al. 2012; Giosan et al. 2012).

While there is still no consensus on what it might have meant for Indus populations, there is now growing evidence of a significant shift across the region occupied by the Civilisation *c.*2200-2000 BC. A new isotopic record from Lake Kotla Dahar demonstrates an abrupt and significant decline in summer monsoon rainfall at this time over southern Haryana (Dixit et al. 2014). This proxy record provides direct and proximate evidence for summer rainfall decline in an area heavily occupied by Indus Civilisation settlements. This shift coincides with pollen and phytolith evidence for particularly arid conditions in Gujarat (Farooqui and Prasad 2013; Prasad et al. 2014) and more broadly, evidence for significant monsoon weakening in isotopic records from the Indus delta and north-eastern India (Staubwasser 2003; Berkelhammer et al. 2012). Together, these records provide clear evidence for a broad-scale weakening in the Indian Summer Monsoon (ISM) over the region occupied by the Indus Civilisation at *c.*2200-2000 BC.

It is therefore relevant and useful to ask how this shift affected Indus Civilisation settlements, both collectively and individually. This includes asking to what extent different settlements were able to adapt. It is clear from the nature and diversity of subsistence practices that Indus settlements were already adept at employing agricultural strategies designed to cope with their particular local environmental conditions (Fuller and Madella 2001; Weber et al. 2010; Petrie et al. in prep/press). There are also suggestions from the archaeobotanical record that populations living in some Indus settlements may have altered their cropping patterns at or around the time of monsoon weakening, and these changes have frequently been posited as an adaptive response to declining water availability (e.g. Madella and Fuller 2006; Prasad et al. 2014; Pokharia et al. 2014).

Although the inferences of causality remain at this stage speculative, this evidence for locally-variable agricultural strategies–which in some cases changed over time–demonstrates that Indus settlements were capable of employing flexible agricultural strategies attuned to local environmental conditions. This provides every reason to hypothesise that Indus settlements actively implemented adaptive responses designed to mitigate impacts of the monsoon decline on agricultural water supply. Until now, however, there have been no attempts to directly test this hypothesis, nor to explicitly compare the extent to which Indus settlements were able to implement adaptive responses. Given the wide variability in climatic, ecological and hydrological conditions across the region, it is highly likely that different settlements both faced different levels of climatic impact, and had different options for adaptation available (Petrie et al. in prep/press). Recognising this variability is critical in any discussion of climate adaptation in the Indus region; and testing the comparative adaptive success of Indus settlements in contrasting ecological settings is a key aim of our study of crop water stress at Indus Civilisation settlements.

Using the conceptual framework outlined in this paper, this ongoing study employs carbon isotope analysis to directly test for evidence that populations in Indus Civilisation settlements adapted to the specific impacts of climate change on crop water supply. Here, we focus on three of these settlements–Harappa, Dabli-vas-Chugta and Masudpur VII (Fig.04)-as a means of illustrating our overall approach. Each of these experienced different rainfall regimes, are supported by different hydrological systems, and employed different agricultural strategies (Weber 2003; Weber et al. 2010; Bates 2015; Petrie et al. in prep/press). Each may, therefore, have suffered different magnitudes of climatic impact on their agricultural water supply, and may have had differing degrees of adaptive capacity.

At each of these settlements, we are testing for evidence of adaptation in the following way:

1. Based on our assessments of sensitivity, predict the magnitude of impact on crop water supply at each settlement in the absence of adaptation.
2. Test whether the magnitude and patterns of impact on crop water supply correspond to

our predictions.

3. Use the results to draw inferences about the extent to which the populations at each settlement adapted to the climatic changes that occurred.

In this context, the first step–predicting climatic impact in the absence of adaptation–requires a comparative assessment of the characteristics that determine the extent to which a given change in rainfall is likely to affect agricultural water supply. Working from the modern literature (Chaudhary and Aggarwal 2009; Field et al. 2014), the key factors are likely to include climatic, ecological and agronomic variables, many of which are similar to those used by Weber *et al*. (2010) and Bates (2015) to characterise different 'agro-ecological zones', or niches. These factors include:

- the baseline amount and distribution of rainfall;
- the magnitude, reliability, timing and accessibility of surface water resources;
- the magnitude, reliability and accessibility of groundwater resources;
- average and extreme temperature ranges;
- soil water holding capacity;
- the water requirements of the crop assemblage;
- the diversity of the crop assemblage, particularly in terms of water requirements and season of growth.

The three sites chosen for our study vary significantly in many of these characteristics, set out in Table 1. Dabli-vas-Chugta and Masudpur VII are both small village sites excavated as part of the *Land, Water and Settlement* project (Petrie, Singh, and Singh 2009; Singh et al. 2012; Petrie et al. in prep/press); while Harappa is an urban site, most recently excavated by the *Harappa Archaeological Project* (e.g. Meadow and Kenoyer 2005; Meadow and Kenoyer 2008). While the characteristics in Table 1 are primarily based on modern climatic and geographical data, we consider they nonetheless provide a reasonable basis for comparison, as there is no evidence to suggest that the relative distribution of rainfall or water resources has changed over the past 4000 years to a degree that would affect our general comparative assessments.

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Harappa is the site furthest west, in the central Punjab. It receives the lowest rainfall of the three, but the highest percentage of winter rain. In terms of landscape position and access to water resources, it provides a clear contrast to the other sites. Lying on a terrace above the Ravi River, one of the major Indus tributaries, Harappa has access to significant and perennial riverine water resources. While over-bank flooding mostly occurs in summer, ox-bow lakes and perennial river flows provide the potential for significant water storage and year-round water supply (Weber et al. 2010). The soils are mainly silt-loams, providing relatively high fertility and water holding capacity, contributing further to the generally relatively favourable agricultural environment. Winter bread wheat and barley appear to have been the mainstays of the Harappan crop assemblage, although a limited range of summer crops were also cultivated and crop diversity increased through the Mature and Late Harappan periods (Weber 2003).

Dabli-vas-Chugta, furthest south, lies close to the margins of the Thar Desert. Today, it receives marginally more rainfall than Harappa, but has limited access to water resources, with low energy summer flooding from ephemeral channels of the Ghaggar the primary source (Neogi 2013). The sandy soils are also comparatively low in fertility, with poor water holding capacity, overall creating a relatively fragile environmental context for agriculture. Its crop assemblage appears to have been relatively limited, with barley the most dominant taxon (Bates 2015).

Masudpur VII, furthest east, is the wettest of the settlements, receiving nearly 500mm annual rainfall today. This is heavily concentrated in summer, but due to the higher overall average, winter rainfall deficit is less pronounced than at Dabli-vas-Chugta. Lying on a continuous alluvial plain crossed by multiple ephemeral monsoon channels, summer monsoon flooding would have occurred around Masudpur VII (Neogi 2013), providing an additional potential source of agricultural water supply. The soils range from silt- to clay-loams, with low-moderate fertility (Neogi 2013). Its crop assemblage suggests an agricultural strategy well-adjusted to the high percentage of summer water availability, with a more diverse assemblage that includes significant proportions of summer crops, including drought-tolerant millets (Bates 2015).

On the basis of these characteristics, we predict that, in the *absence* of adaptive response, the weakening of the ISM *c.* 2200-2000 BC would have caused a reduction in crop water supply at all sites. This should be evident in the $\delta^{13}C$ of both summer and winter crops excavated from these sites (assuming that the excavated crop remains were at least principally cultivated on a relatively local basis). Winter rainfall is not connected to the ISM, and changes in winter rainfall patterns around *c.*2200-2000 BC are less certain (Petrie et al. in prep/press). However, given the importance of summer rainfall for the replenishment of both soil moisture and any stored water resources (Chaudhary and Aggarwal 2009), a significant weakening of the ISM could be expected to reduce winter, as well as summer crop water supply. We therefore predict that if no adaptive responses were employed, crop water availability would have declined in both summer and winter crops at all three sites.

However, again in the absence of adaptive response, we predict that crop water supply would be most affected at Dabli-vas-Chugta. This is because although its modern rainfall is marginally higher than at Harappa, the size and variety of its options for agricultural water supply are far more limited. It relies heavily on flooding from summer monsoon rains, and this would have almost certainly been significantly affected by the shift in the ISM. While the locally plentiful groundwater could have offered a potential alternative water supply, we currently lack evidence to suggest that Indus settlements exploited groundwater for agriculture and for the purposes of our predictions, we assume this was not utilised at Dabli-vas-Chugta.

We predict the next most significant reduction in crop water supply at Masudpur VII. This site's higher baseline rainfall, and greater soil water holding capacity, renders its agricultural water supply less sensitive than that at Dabli-vas-Chugta. However, given the lack of obvious surface water resources, and presumed reliance on summer rain and simple management of ephemeral monsoon floods, its agricultural water supply would nonetheless have been vulnerable to declining inputs from monsoon rains.

The lowest impacts are expected at Harappa. Models of river flows suggest that Harappa's surface water resources would have been affected by the declining ISM–indeed, modelled reductions in mean annual discharge of the Beas River, close to Harappa, are in the order of 20% (Wright et al. 2008). As such, some impacts on crop water supply could be expected, but are likely to be comparatively low, given the greater volume, reliability and diversity of surface water available. Geomorphological evidence suggests shifting river channels in Harappa's vicinity may also have offered new challenges and/or opportunities for water supply around the same time (Pendall and Amundson 1990; Wright et al. 2008) but the overall trend is still expected to be a decline. Finally, models suggest that winter rainfall did not suffer a prolonged decline at Harappa (Wright et al. 2008), potentially helping to buffer the important winter wheat and barley crops from declining monsoon-fed water resource availability. As such, while we still predict that crop water supply at Harappa would have been affected by the climate event at *c.*2200-2000 BC, we suggest that of the sites, its agricultural water supply was least sensitive to this climatic shift.

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We are currently in the process of testing these predictions using stable carbon isotope analysis of crop remains from each of these sites, as part of a broader study of crop water stress at Indus Civilisation settlements (Jones *et al.* in prep). This will enable us to directly test our predictions, and to hence to establish:

1. Whether there is any evidence that the climate event *c.* 2200-2000 BC had a detrimental impact on agricultural water supply at any of these sites.
2. If so, whether this impact was of the magnitude that we predicted in the absence of any adaptive response, or whether instead there is evidence of adaptation leading to full or partial mitigation; and
3. Whether the pattern of impacts across sites is suggestive of differential success in adaptation at different settlements.

Conclusions

This combination of a framework with which to model climatic sensitivity, predict climatic impacts in the absence of adaptation, and finally test for adaptation through a direct assessment of trends in agricultural water supply will enable, for the first time, an explicit assessment of both the impacts of climate change on Indus Civilisation settlements, and the extent to which different settlements were able to adapt. We hope that this will both further understanding of the tangible impacts of climate change on Indus Civilisation settlements, and, importantly, stimulate a discussion of adaptation to climate change in the Indus region which is firmly grounded in empirical data employed within a clear theoretical framework. More broadly, we hope that the framework we propose for testing adaptation to climate change promotes a more nuanced approach to discussions of climatic impacts and adaptation in the Indus and beyond–one which recognises and explores the variability between settlements in both exposure to climatic risks and their capacity to adapt, and which seeks to find a means of directly assessing adaptation to climate change in the archaeological record.

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Bibliography

Aguilera, Monica, Juan P. Ferrio, José L. Araus, Josep Tarrús, and Jordi Voltas. 2011. “Climate at the Onset of Western Mediterranean Agriculture Expansion : Evidence from Stable Isotopes of Sub-Fossil Oak Tree Rings in Spain.” Palaeogeography, Palaeoclimatology, Palaeoecology 299: 541–51.

An, Li, and David López-Carr. 2012. “Understanding Human Decisions in Coupled Natural and Human Systems.” Ecological Modelling 229: 1–4.

Araus, J., Anna Febrero, Ramón Buxó , Maria O. Rodriguez-Arizac, Fernando Molinac, Maria D. Camalich, Dimas Martın, and Jordi Voltas. 1997. “Identification of Ancient Irrigation Practices Based on the Carbon Isotope Discrimination of Plant Seeds: A Case Study from the South-East Iberian Peninsula.” Journal of Archaeological Science 24: 729–40.

Araus, José L., Anna Febrero, Miquel Catala, Miquel Molist, Jordi Voltas, and Ignacio Romagosa. 1999. “Crop Water Availability in Early Agriculture: Evidence from Carbon Isotope Discrimination of Seeds from a Tenth Millennium BP Site on the Euphrates.” Global Change Biology 5: 201–12.

Araus, J.L., Dolors Villegas, Nestor Aparicio, L.F. Garcı, S. El Hani, Yahia Rharrabti, Juan P. Ferrio, and Conxita Royo. 2003. “Environmental Factors Determining Carbon Isotope Discrimination and Yield in Durum Wheat under Mediterranean Conditions Plant Materials and Experimental Design.” Crop Science 43: 170–80.

Araus, José L., Juan P. Ferrio, Jordi Voltas, Mònica Aguilera, and Ramón Buxó. 2014. “Agronomic Conditions and Crop Evolution in Ancient Near East Agriculture.” Nature Communications 5: 3953.

Bates, Jennifer. 2015. “Social Organisation and Change in Bronze Age South Asia: A Multi-Proxy Approach to Urbanisation, Deurbanisation and Village Life through Phytolith and Macrobotanical Analysis.” PhD diss., University of Cambridge.

Berkelhammer, Max, Ashish Sinha, Linda Stott, Hai Cheng, Francesco S.R. Pausata, and Kei Yoshimura. 2012. “An Abrupt Shift in the Indian Monsoon 4000 Years Ago.” Geophysical Monograph Series 198: 75–87.

Brooks, Nick. 2006. “Cultural Responses to Aridity in the Middle Holocene and Increased Social Complexity.” Quaternary International 151: 29–49.

Brooks, Nick, Neil Adger, and Mick P. Kelly. 2005. “The Determinants of Vulnerability and Adaptive Capacity at the National Level and the Implications for Adaptation.” Global Environmental Change 15: 151–63.

Chaudhary, Anita, and P.K. Aggarwal. 2009. “Impact of Climate Change on Food Security of India.” In Proceedings of the International Conference on Energy and Environment, 22–25.

Cronin, Thomas M. 2010. Palaeoclimates: Understanding Climate Change Past and Present. New York.

Dawson, Todd E., Stefania Mambelli, Agneta H. Plamboeck, Pamela H. Templer, and Kevin P. Tu. 2002. “Stable Isotopes in Plant Ecology.” Annual Review of Ecological Systematics 33: 507–59.

Dixit, Yama, David A. Hodell, and C.ameron A. Petrie. 2014. “Abrupt Weakening of the Summer Monsoon in Northwest India 4100 Yr Ago.” Geology, G35236.1.

Farooqui, Anjum, and Vandana Prasad. 2013. “Climate, Vegetation and Ecology during Harappan Period: Excavations at Kanjetar and Kaj, Mid-Saurashtra Coast, Gujarat.” Journal of Archaeological Science 40: 2631-2647.

Farquhar, Graham D., Joseph R. Ehleringer, and Kerry T. Hubick. 1989. “Carbon Isotope Discrimination and Photosynthesis.” Annual Review of Plant Physiology and Plant Molecular Biology 40: 503–37.

Farquhar, Graham D., Marion H. O’Leary, and Joseph A. Berry. 1982. “On the Relationship between Carbon Isotope Discrimination and the Inter-Cellular Carbon-Dioxide Concentration in Leaves." Australian Journal of Plant Physiology 9: 121–37.

Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, K.L. Chatterjee, et al. 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge.

Folke, Carl. 2006. "Resilience: The Emergence of a Perspective for Social–ecological Systems Analyses." Global Environmental Change 16: 253–67.

Fuller, Dorian Q., and Marco Madella. 2001. "Issues in Harappan Archaeobotany: Retrospect and Prospect." In Indian Archaeology in Retrospect, Volume II. Protohistory, edited by S. Settar and K. Korisettar, 317–90. New Dehli.

Gallopín, Gilberto C. 2006. "Linkages between Vulnerability, Resilience, and Adaptive Capacity." Global Environmental Change 16: 293–303.

Gill, Richardson B., Paul A. Mayewski, Johan Nyberg, Gerald H. Haug, and Larry C. Peterson. 2007. "Drought and the Maya Collapse." Ancient Mesoamerica 18: 283–302.

Giosan, Liviu, Peter D. Clift, Mark G. Macklin, Dorian Q. Fuller, Stefan Constantinescu, Julie A. Durcan, Thomas Stevens, et al. 2012. "Fluvial Landscapes of the Harappan Civilization." Proceedings of the National Academy of Sciences of the United States of America 109: E1688–94.

Gronenborn, Detlef, Hans-Christoph Strien, Stephan Dietrich, and Frank Sirocko. 2014. "'Adaptive Cycles' and Climate Fluctuations: A Case Study from Linear Pottery Culture in Western Central Europe." Journal of Archaeological Science 51: 73–83.

Haug, Gerald H., Detlef Günther, Larry C. Peterson, Daniel M. Sigman, Konrad A. Hughen, and Beat Aeschlimann. 2003. "Climate and the Collapse of Maya Civilization." Science 299: 1731–35.

Lorenz, Daniel F. 2010. "The Diversity of Resilience: Contributions from a Social Science Perspective." Natural Hazards 67: 7–24.

MacDonald, Glen. 2011. "Potential Influence of the Pacific Ocean on the Indian Summer Monsoon and Harappan Decline." Quaternary International 229: 140–48.

Madella, Marco., and Dorian Q. Fuller. 2006. "Palaeoecology and the Harappan Civilisation of South Asia: A Reconsideration." Quaternary Science Reviews 25: 1283–1301.

Meadow, Richard, and J. Mark Kenoyer. 2008. "Harappa Excavations 1998-1999: New Evidence for the Development and Manifestation of the Harappan Phenomenon." In South Asian Archaeology 1999, edited by E.M. Raven, 85–109. Leiden.

Meadow, Richard, and J. Mark Kenoyer. 2005. "Excavations at Harappa 2000-2001: New Insights on Chronology and City Organization." In South Asian Archaeology 2001, edited by C.N. Jarriage and V. Lefèvre, 207–25. Paris.

Mitchell, Peter. 2008. "Practising Archaeology at a Time of Climatic Catastrophe." Antiquity 82:

1093–1103.

Neogi, Sayantani. 2013. “Geoarchaeological Investigations of Indus Settlements in the Plains of North-Western India.” PhD diss., University of Cambridge.

Orlove, Ben. 2005. “Human Adaptation to Climate Change: A Review of Three Historical Cases and Some General Perspectives.” Environmental Science & Policy 8: 589–600.

Pandey, D.A., Anil K. Gupta, and David M. Anderson. 2003. “Rainwater Harvesting as an Adaptation to Climate Change.” Current Science 85: 46–59.

Pendall, Elise, and Ronald Amundson. 1990. “Soil/landform Relationships Surrounding the Harappa Archaeological Site, Pakistan.” Geoarchaeology 5: 301–22.

Petrie, Cameron A., Ravindra N. Singh, and Arvind K. Singh. 2009. “Investigating Changing Settlement Dynamics on the Plains: The 2009 Survey and Excavations at Masudpur (Hissar District, Haryana.” Puratattva 39: 38–49.

Petrie, Cameron A., Ravindra N. Singh, Charly A.I. French, Jennifer Bates, Penelope J. Jones, Carla Lancelotti, Frank Lynam, Sayantani Neogi, A.K. Pandey, Danika Parikh, Vikas Pawar, and David I. Redhouse. “Adaptation to Variable Environments, Resilience to Climate Change.” Current Anthropology in press/prep.

Pokharia, Anil K., Jeewan Singh Kharakwal, and Alka Srivastava. 2014. “Archaeobotanical Evidence of Millets in the Indian Subcontinent with Some Observations on Their Role in the Indus Civilization.” Journal of Archaeological Science 42: 442–55.

Ponton, Camilo, Liviu Giosan, Tim I. Eglinton, Dorian Q. Fuller, Joel E. Johnson, Pushpendra Kumar, and Tim S. Collett. 2012. “Holocene Aridification of India.” Geophysical Research Letters 39: L03704.

Possehl, Gregory L. 1997. “The Transformation of the Indus Civilization.” Journal of World Prehistory 11: 425–72.

Prasad, Vandana, Anjum Farooqui, Anupam Sharma, Binita Phartiyal, Supriyo Chakraborty, Subhash Bhandari, Rachna Raj, and Abha Singh. 2014. “Mid–late Holocene Monsoonal Variations from Mainland Gujarat, India: A Multi-Proxy Study for Evaluating Climate Culture Relationship.” Palaeogeography, Palaeoclimatology, Palaeoecology 397: 38–51.

Riehl, Simone, Konstantin E. Pustovoytov, Heike Weippert, Stefan Klett, and Frank Hole. 2014. “Drought Stress Variability in Ancient Near Eastern Agricultural Systems Evidenced by δ13C in Barley Grain.” Proceedings of the National Academy of Sciences of the United States of America, 111: 12348-12353.

Singh, Ravindra N., Cameron A. Petrie, Charly A.I. French, Jennifer Bates, A.K. Pandy, Danika Parikh, Carla Lancelotti, and David I. Redhouse. 2012. “Survey and Excavations at Dabli-Vas Chugta, Hanumangarh District, Rajasthan.” Puratattva 42: 133–47.

Smit, Barry, and Johanna Wandel. 2006. “Adaptation, Adaptive Capacity and Vulnerability.” Global Environmental Change 16: 282–92.

Staubwasser, Michael. 2003. “Climate Change at the 4.2 Ka BP Termination of the Indus Valley

Civilization and Holocene South Asian Monsoon Variability.” Geophysical Research Letters 30: 1425-1430.

Staubwasser, Michael, and Harvey Weiss. 2006. “Holocene Climate and Cultural Evolution in Late Prehistoric–early Historic West Asia.” Quaternary Research 66: 372–87.

Van de Noort, Robert. 2011. “Conceptualising Climate Change Archaeology.” Antiquity 85: 1039–48.

Wallace, Michael, Glynys Jones, Mike Charles, Rebecca Fraser, Paul Halstead, Timothy H.E. Heaton, and Amy Bogaard. 2013. “Stable Carbon Isotope Analysis as a Direct Means of Inferring Crop Water Status and Water Management Practices.” World Archaeology 45: 388–409.

Weber, Steven. 2003. “Archaeobotany at Harappa: Indications of Change.” In Indus Ethnobiology: New Perspectives from the Field, edited by Steven Weber and William R. Belcher, 175–98. Maryland.

Weber, Steven, Tim Barela, and H. Lehman. 2010. “Ecological Continuity: An Explanation for Agricultural Diversity in the Indus Civilization and beyond.” Man and Environment XXXV: 62–75.

Widgren, Mats. 2012. “Climate and Causation in the Swedish Iron Age: Learning from the Present to Understand the Past.” Geografisk Tidsskrift-Danish Journal of Geography 112 (2): 126–34.

Wright, Rita P., Reid A. Bryson, and Joseph Schuldenrein. 2008. “Water Supply and History: Harappa and the Beas Regional Survey.” Antiquity 82: 37–48.

Zhang, Cong-zhi, Jia-bao Zhang, Bing-zi Zhao, Hui Zhang, and Ping Huang. 2009. “Stable Isotope Studies of Crop Carbon and Water Relations : A Review.” Agricultural Sciences in China 8: 578–90.