MEGADROUGHT AND COLLAPSE

From Early Agriculture to Angkor

EDITED BY HARVEY WEISS

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Megadrought, Collapse, and Causality

HARVEY WEISS

Recent discoveries of megadroughts, severe periods of drought lasting decades or centuries, during the course of the Holocene have revolutionized our understanding of modern climate history. Through advances in paleoclimatology, researchers have identified these periods of climate change by analyzing high-resolution proxy data derived from lake sediment cores, marine cores, glacial cores, speleothem cores, and tree rings. Evidence that megadroughts occurred with frequency and abruptly over the last 12,000 years, a timespan long assumed to be stable compared to earlier glacial periods, has also altered our understanding of societies' trajectories. The fact that severe, multi-decadal or century-scale droughts coincided with societal collapses well known to archaeologists has challenged established multi-causal analyses of these events. Megadroughts, impossible to predict and impossible to withstand, may have caused political collapse, regional abandonment, and habitat tracking to still-productive regions. The nine megadrought and societal collapse events presented in this volume extend from the foraging-to-agriculture transition at the dawn of the Holocene in West Asia to the fifteenth-century AD collapse of the Khmer Empire in Angkor (Cambodia). Inevitably, this collection of essays also raises challenges to causal analyses of societal collapse and for future paleoclimatic and archaeological research.

MEGADROUGHTS ARE REAL. Very difficult drought conditions in the western United States, apparent fifteen years ago, have approached megadrought (Cook et al. 2004; Kogan & Wei 2015). In the past, megadroughts spanned more than a decade to several centuries. They covered wide expanses of territory defined by the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation and monsoons (some globally teleconnected) that delivered regional precipitation, and they had characteristic precipitation reductions, with abrupt or gradual onsets and terminations (Meehl & Hu 2006; Sinha et al. 2011; Lake 2011). Megadroughts are now well documented in Africa (Verschuren, Laird, & Cumming 2000; Maley & Vernet 2015), India (Sinha et al. 2011), East Asia (Cook et al. 2010), the Andes (Ledru et al. 2013; Thompson et al. 2013), Europe and the Mediterranean (Cook et al. 2015), and North America (Cook et al. 2004; Stahle et al. 2007).

Over the past millennium alone, especially during the eleventh to fifteenth centuries in Europe and North America, megadroughts have been abrupt, severe, extensive, and prolonged (Asmeron et al. 2013; Cook et al. 2014, 2015.) Then and still earlier, megadroughts forced societal collapse: they presented insurmountable obstacles in rainfed-agriculture regions and reduced river flow conditions in irrigation-agriculture regions, thereby undermining the economy and political structure of agriculture dependent societies. The collapse of such societies, evident archaeologically and historically, manifested as political and social disintegration and the abandonment of drought-stricken regions accompanied by migration, or habitat tracking, to agriculture sustaining landscapes. However, the coincidence of megadrought and societal collapse is a recent discovery within archaeology and paleoclimatology and far from completely described and understood. As a contribution toward that understanding, this volume details nine past major megadroughts and societal collapses, from the origins of agriculture in the Near East 12,000 years ago to the demise of Angkor in Cambodia in the fifteenth century AD.

Studies of postglacial Holocene climate history and archaeology have been converging for some thirty years. Beginning in the 1970s and '80s, paleoclimate researchers' attention was drawn increasingly to the transition from the glacial Pleistocene to the post-Pleistocene—that is, the modern, or Holocene, period. The nature of that transition, thought to be gradual in the 1950s, was revealed through analyses in the early 1990s of the Greenland ice cores—especially GISP2 (Greenland Ice Sheet Project 2)—to be an abrupt climate change known as the Younger Dryas event (Alley et al. 1993). The rapidity of that event, and especially its abrupt decadal terminus and the onset of fully modern postglacial conditions, was a geological surprise that would set the stage for further research into the nature of global Holocene climates. Revelation of the dynamic qualities of the post-Younger Dryas climates of the modern or Holocene period and their global or regional punctuation by periods of megadrought, decadal- and century-scale abrupt climate changes previously unknown, has been a major achievement of the past few decades of research.

Paleoclimate Revolution

The major tools in the paleoclimate revolution are paleoclimate proxy data retrieved from natural long-term archives. The archives are the sedimentary deposits on ocean floors, lake floors, drip water created stalagmites in caves, annual snowfall laminations on glaciers, and annual growth rings on trees. Each of these five types of natural archives preserves sequences of isolable and datable intervals of deposition or growth that provide proxies for different kinds of climate conditions. Lake bottom sediments, for instance, preserve in oxygen-free conditions the annual pollen from lake-shore plant life, and thus record the datable and climate specific changes in lake-shore plant pollen (Zolitschka 2007; Ojala et al. 2012). Similarly, ocean cores preserve the microscopic diatoms that are specific to temperature conditions, or terrestrial dust derived from places subject to arid conditions, or tephra deposits windblown into the oceans from specific volcanoes (Hughen & Zolitschka 2007). Accumulations of ceiling drip on cave floors preserve in stalagmites, or speleothems, the mineral content of the water above the cave. That mineral content includes minute amounts of stable oxygen and carbon isotopes, which are indicators of both humid conditions and temperature above the cave at the specific time of the incremental cave drips (Lachniet 2009; Wong & Breecker 2015). The ring width of annual growth observed in trees, a variable determined by precipitation and temperatures levels, also provides a precisely dated climate record (Hughes et al. 2011; Salzer et al. 2013). Mapping the distribution through space and time of tree-ring sequences (with annual resolution dating) has proven to be a key identifier of megadroughts through the past two millennia across North America, Europe, and Asia (Cook et al. 2004; 2007; 2010; 2015). Lastly, glaciers preserve the annual laminations of snow at high latitudes and high tropical elevations. The isotopic composition of the oxygen in the ice identifies the sea surface temperature of the water's source, as well as precipitation, while major ions such as ammonium and nitrate unravel regional atmospheric circulation variability, and sulfate concentrations mark datable volcanic eruptions (Alley et al. 1993; Severinghaus, et. al. 1998; Vimeux et al. 2009; Thompson et al. 2013). Each of these five paleoclimate proxies has provided new and essentially revolutionary evidence based on high-resolution dating of megadroughts from the end of the Pleistocene (the last glacial ages) through the modern period.

Archaeological Studies of Societal Collapse

While this revolution in the earth's climate history has evolved, archaeologists have been moving from a post-World War II fascination with the social evolutionary processes that surrounded the genesis of civilizations to a concern for their periodic terminations or collapse. Societal collapses appear in the archaeological record as political devolution, urban abandonment and settlement dispersal, regional abandonment, and migration (or habitat tracking) to sustainable environments. Interest in societal collapse accelerated in the late 1970s and 1980s. One manifestation, prompted by C. S. Holling (1973), was Robert Adams's analysis of Mesopotamian collapses, which focused on the role of economic maximization policies in weakening societies' adaptive capacities (1978). A second early influence was research by Michael Moseley and his colleagues into the natural causes of Andean societal collapses (Moseley & Deeds 1982; Moseley et al. 1983). By the late 1980s, the evolving interest in collapse was synthesized in the publication of two volumes (Tainter 1988; Cowgill & Yoffee 1988) that broadly sought to select cogent examples of collapse and to synthesize the then current explanations for them. In the edited volume by George Cowgill and Norman Yoffee (1988), the nature of collapse was defined in uncertain terms, but where possible the explanatory forces were deemed mostly internal, endogenous processes surrounding resource exploitation, population pressure, warfare, and societal dysfunctions. In no case were climate changes addressed as causes of collapse, and "climate" did not appear in the volume's index. Joseph Tainter (1988) argued that climate change as a societal collapse force never occurred, and that in the cases he addressed the law of diminishing returns operated on societal scales to induce collapse. He dismissed the usual, countervailing roles territorial expansion, resource expansion, and technological innovation played against diminishing returns in the production process.

The study of collapse was redirected vigorously in the early 1990s with the publication of four forays into Holocene climate research. Izumi Shimada and Lonnie Thompson linked the collapse of the Moche state in the north Andes to annual lamination Quelccaya ice-core records of a "series of severe sixth-century droughts, including one of the severest droughts of the past 1,500 years, spanning AD 562 to 594" (Shimada et al. 1991). Charles Ortloff and Alan Kolata (1993) linked the collapse of the Tiwanaku state on the shores of Lake Titicaca (Bolivia) to a major twelfth-century AD drought event recorded nearby in the Quelccaya glacial core, as well as in the lake's sediment cores. Harvey Weiss and colleagues (1993) linked the 2200 BC Akkadian Empire collapse in Mesopotamia, and synchronous collapses from the Aegean to the Indus, with local evidence for a two- or three-century drought episode hypothesized to have been interregional. David Hoddell, Jason Curtis, and Mark Brenner (1995) retrieved and analyzed a lake sediment core in Guatemala and discovered a major drought event that was synchronous with the eighth century AD Maya collapse. The Akkadian and Maya collapse studies received significant public and scientific attention. The Hoddell, Curtis, and Brenner article was published with a cautionary prefatory note by a Mayan archaeologist questioning the role of climate change and drought in societal collapse. Cautionary comments from other archaeologists also prefaced the article by Weiss and colleagues. The worlds of archaeology and climatology had converged—uneasily—on abrupt, century-scale climate change, megadroughts, and societal collapses.

Twenty-first Century Studies of Megadrought and Collapse

The research has advanced and retreated since. Peter deMenocal (2001) and Weiss and Raymond Bradley (2001) drew attention in the journal *Science* to the new and numerous paleoclimate data synchronous with societal collapse. deMenocal's survey was the first to emphasize new megadrought-specific and El Niño data linked to records of societal collapse. Weiss and Bradley stressed the adaptive quality of societal collapse in the face of insurmountable climate degradation and extended their findings to modern climate-change challenges. A popular volume by Jared Diamond (2005) offered a synthetic treatment of causes for some societal collapses, though it failed to capture the essence of the new Holocene paleoclimatology. Diamond assigned collapse to multiple causes, including "unsustainable" societal decisions, such as exhausting resources, generating warfare, diminishing the agricultural base, and overpopulating.

New paleoclimatic and archaeological data for Holocene climate changes synchronous with societal collapse continued to generate strong reactions among some archaeologists, who understood such research to be an elective ideological stance, a backward step to the discredited "climate determinism" popularized in the early twentieth century by Ellsworth Huntington, a history lecturer at Yale University (Huntington 1907; 1915). Huntington had promoted, with scant archaeological and paleoclimate data, the notion that climate alone had determined the demise of several civilizations, just as he had determined the nature of their cultures, lazy and slow-thinking in the tropics, energetic and sharp-thinking in northern latitudes. Huntington's thesis was rejected as too simple and, in Owen Lattimore's mocking words, as "the romantic explanation of hordes of erratic nomads, ready to start for lost horizons at the joggle of a barometer in search of suddenly vanishing pastures" (Manley 1944).

Warnings about the dangers of climate determinism have since been one strand of response to the steady production of high-resolution paleoclimate data for abrupt and decadal to century-scale change coincident with, and apparently the cause of, region-wide agricultural failures and societal collapses. Such a focus on a purported ideological stance—perhaps at odds with the archaeologists' own deeply held stances—can lead to a myopic view of the testable paleoclimatic and archaeological data for regional settlement and agricultural production. For example, critics of what is deemed "climate determinism" often misinterpret paleoclimate data as indicating minimal climate change during the documented megadroughts (Wilkinson et al. 2007; Roberts et al. 2011; Butzer 2012), misinterpret the archaeological data as indicating minimal evidence for regional collapse, and confuse continuous adaptive occupations with habitat-tracking refugia (Rosen 2007; Schwartz 2007; Kuzucuoğlu 2007). Needless to say, the testing and measurement of all causal factors, including dynamic climatic conditions and societal responses, as well as related social processes, is certainly the goal of modern researchers.

The publication of *Questioning Collapse*, edited by Patricia McAnany and Norman Yoffee (2009) marked a major oppositional step in societal collapse and abrupt climate change studies. Here the new hard data for abrupt Holocene climate change were labeled equivocal and unconvincing, and even the archaeological data for societal collapses, including regional depopulations and abandonments, were denied in a politically correct sweep. In common with other works, paleoclimate data for drought and megadrought were dismissed as merely popular concerns (Tainter 2015). The data were deemed not real, or, if real, certainly not as precise as claimed and largely the product of a current fascination with "climate." In a similar vein, the continued existence of Maya and Ancestral Pueblo peoples—even Christians from northern Iraq, among others—was cited as proof that their ancient societies had not experienced collapse. Indeed, it was suggested that a kind of ethnocentric delusion informed arguments for the collapse of these ancient societies.

In search of explanatory paradigms that address collapse, some archaeologists have recently resurrected "resilience theory." A simple model of ecological systems' responses to stress factors, resilience theory has been applied to social systems and adopted as an explanatory framework for major transitions and transformation, including societal collapse (Holling 1973; Holling & Gunderson 2002; Redman & Kinzig 2003; Redman 2005; Costanza et al. 2007; Faulseit ed. 2016). Resilience, the ability of a social system to adapt to disequilibrating forces or, still more generally, "the ability to maintain, or quickly restore, in the face of a challenge, conditions considered highly desirable" (Cowgill 2012: 304), had been applied before to the long arc of Mesopotamian history, as noted above (Adams 1978). Recent archaeological applications, however, fit phases of social and environmental change into resilience theory's four-phase sequence of "exploitation," "conservation," "release" or "collapse," and "reorganization." The external forces that cause "release" or "collapse" are, of course, as variable as the social and environmental conditions at times of collapse and reorganization. Hence resilience theory "describes a process but fails to explain how the process is transformed" (Kidder et al. 2016: 73). Equally problematic is the incommensurability between resilience theory and the social sciences: agency, conflict, knowledge, and power are absent from resilience theory (Olsson et al. 2015). Similarly, of course, resilience theory lacks a megadrought phase.

One older line of societal collapse analysis exemplified within Karl Butzer's *Archaeology as Human Ecology* (1982), now resynthesized (Butzer 2012), takes coincident multicausality to be essential for societal collapse. This social science theme, that the interplay of multiple factors is almost always more critical than any single factor, is often reprised in societal collapse analyses (Diamond 2005; Costanza et al. 2007), but is now challenged by the new paleoclimate data for megadrought. Political analysts of effective causal forces had long understood, even in the social science of the early twentieth century, that "multiple causes of an event may be out of phase and only have an effect when they occur together" (Feyerabend 2010: 106, citing Lenin 1964). Butzer's claim, for instance, is that coincident multicausality generated the Old Kingdom collapse in Egypt at 2200 BC, or 4.2 ka BP (4200 years ago), which was synchronous with the 2200 BC abrupt megadrought in Mesopotamia (see Weiss, this volume). According to Butzer a "concatenation of triggering economic, subsistence, political, and social forces probably drove Egypt across a threshold of instability, setting in train a downward spiral of cascading feedbacks" (Butzer 2012: 3634). He imagines disruption of international trade, erroneously hypothesized and then dated 100 years too early, and supposes "contending elite groups may originally have used an impending crisis of succession to undermine royal legitimacy, in an effort to steer more power to the provinces" (ibid.). To arrive at this conclusion, Butzer rejects the dating of the palaeoclimate proxies for abrupt onset megadrought: "Considering the partial match of these rough dates, it is possible but unproven that Nile failures may have helped trigger collapse of the Old Kingdom" (ibid.: 3633).

However, the dating is robust for both the Nile flow abrupt reduction (Stanley et al. 2003; Marshall et al. 2011; Blanchet et al. 2013) and the disruptor of the sources of Nile flow, the Indian monsoon. The Indian Monsoon disruption is in fact documented by the highest resolution data available for the 4.2 ka BP (2200 BC) event, from the Mawmluh Cave speleothem (Berkelhammer et al. 2012), and supported by the lower resolution, but nevertheless compelling Kotla Dahar lake sediment core (Dixit, Hodell, & Petrie 2014). The chronology of the subsequent First Intermediate Period, the Egyptian Old Kingdom collapse, is also now robustly radiocarbon dated (Ramsey et al. 2010) and is virtually synchronous with the similarly high-resolution, radiocarbon dated Akkadian Leilan IIc collapse in northern Mesopotamia (Weiss et al. 2012). The megadrought disruption of Nile flow is a certainty at ca. 2200 BC, while multiple other causes hypothesized by Butzer remain undocumented.

A related analysis has relied upon the "correlation is not causality" argument (Coombes & Barber 2005). For example, while the ca. 4.2 ka BP (2200 BC) megadrought was coincident with Egyptian and Mesopotamian collapse, Coombes and Barber argue, there may have been other sufficient and necessary causes—although they simultaneously maintain that synchronous collapse across varied regions supports climate forcing at ca. 2200 BC. However, archaeological data shows that preindustrial human societies could not withstand megadrought, that circumstances rendered irrigation innovations physically impossible, and that they adapted through political collapse and migration to sustainable environments. Other ancillary causes are either not documented or seem minor. In most cases of megadrought, the stricken societies analyzed in this volume, including the Natufian, Anatolian Neolithic villages, Akkadian Empire, Late Bronze Age eastern Mediterranean, Teotihuacan, Ancestral Pueblo, and Angkor, were manifestly unsustainable when unpredicted megadrought occurred. Some pre-collapse environmental or social stressors have long been suggested for the Maya and Tiwanaku cases discussed here, but these forces have receded as causal explanations to ancillary or possibly superfluous amplifier status compared to megadrought, which brings unmitigated vegetation die-off and precludes nonlinear societal responses (Breshears et al. 2005).

Present and Future Studies of Megadrought and Collapse

In view of the recent history of research, discussions, and analysis, the function of this volume is to synthesize advances in the most prominent archaeological and historical situations where abrupt climate changes--specifically megadroughts—and societal collapses have coincided in a causal link. To be sure, varieties of evidence are required to identify abrupt megadrought as a causal force in societal collapse. Societal collapse must be observed, defined, and measured in the archaeological record, and coincident abrupt climate change must be observed and measured in the paleoclimate record. Abruptness, magnitude, and duration appear to be the important paleoclimate variables, since they co-occur at levels that made collapse inevitable due to the unavailability in some circumstances of natural or social tools and resources with which to counter the effects of megadrought upon local subsistence resources and technologies (Dillehay & Kolata 2004). In such situations the stress of reduced subsistence resources, cultivable landscapes, and agricultural production forces adaptive regional abandonment, migration, or habitat tracking, to accessible agricultural refugia. The archaeological and palaeoclimatic challenge is to define predictive levels of megadrought abruptness, magnitude, and duration relative to pre-abrupt climate change social and nautral resources.

In several cases discussed in this volume, megadrought is not the only disruptive causal force in evidence archaeologically or historically at the time of collapse. Or, megadrought itself generates other causes that promote societal collapse. Here we enter the delicate arena of weighing multiple causal factors, or factors elicited in the search for multiple causal factors. In a variety of situations, for example, short-term drought is understood to be a natural condition that can provoke famine, a social condition, and underscores the well-documented societal variables that mediate reduced agricultural production and distribution (Davis 2001). In some cases, a mode of subsistence alteration, from agriculture to pastoral nomadism, from millet to cereal farming, or multi-cropping, provides resilience and is also visible or suggested within the megadrought affected societies (see, for example, Petrie et al. 2016).

Also addressed in this volume are the termination of megadrought and variable societal responses, from resettlement to permanent relocation, to the return of pre-megadrought climatic and environmental conditions. The most salient examples of that variability are the essentially unexplained, opportunistic Amorite resettlement of northern Mesopotamia (Weiss 2014), the continued post-collapse desertion of the central Maya lowlands (Turner & Sabloff 2012), and the post-collapse population dispersal at Angkor (Lucero, Fletcher, & Coningham 2015). Adaptation and sustainability, alongside resilience or culturally perceived viability, remain, therefore, key processes in these societal collapses and post-collapse transformations.

These observations ultimately raise two questions, however. What is the weight of megadrought climate change in the causal nexus of societal collapse? And would collapse have occurred without megadrought? One path toward resolution of these questions might be the careful replacement of the loose archaeological usage "cause," with its array of descriptive and functional subcategories. As Nancy Cartwright has noted, "One factor can contribute to the production or prevention of another in a great variety of ways. There are standing conditions, auxiliary conditions, precipitating conditions, agents, interventions, contraventions, modifications, contributory factors, enhancements, inhibitions, factors that raise the number of effects, factors than only raise the level, etc." (1999: 119). The archaeological challenge, of course, would be tests of the verisimilitude of such categorizations. Another analytic path forward might be the quantified and modeled simulation of societal trajectories using archaeological chronologies, paleoclimate data, subsistence and settlement pattern data (Altaweel 2008, Axtell et al. 2002, d'Alpoim Guedes et al. 2016, Weiss & Booth 2014). Of course, such simulations would only be as useful as their data resolution and their models' verisimilitude. A third path might be the deployment of influence diagrams (Howard & Matherson 2005; Pearl 2000) with highly resolved archaeological data. These quantitative measures might allow us to begin to weigh causes beyond the unlikely multicausal democracy presumed within "concatenated events."

The nine examples presented in this volume extend from the terminal Pleistocene to the Little Ice Age, and from Southeast Asia to West Asia, the Mediterranean, the US Southwest, Mesoamerica, and the Andes. Each case has been the subject of prominent and numerous earlier analyses and publications, but is reexamined in detail here. In each case, the researchers explore the role of abrupt megadrought climate change in societal collapse and set the stage for further research, both within these examples and other cases yet untreated in detail.

The Collapse of Foraging and Introduction of Cultivation 12,800–11,500 Years Ago

The origins of agriculture occurred independently at several times and places during the Holocene, but first appeared in the West Asia with the early transition from foraging to cultivation and then to farming in the Levant region of Israel, Palestine, and western Syria. This West Asian trajectory from foraging to full-blown agriculture took at least 20,000 years, across the span from the Late Glacial Maximum to the Holocene. Not until the end of the Pre-Pottery Neolithic A period, ca. 11,000 years ago, is the evidence of genetic selection and domestication visible in archaeobotanical assemblages.

Archaeological and paleoclimate research has focused much attention on the hunter-gatherer-forager transition to early cultivation (the sowing and harvesting of wild plants in tilled soil)—the first step towards eventual plant domestication and farming within sedentary agricultural villages (Willcox, Nesbitt, & F. Bittman 2012). It was the discovery of the Younger Dryas Period event that marked a new phase in both paleoclimate and origins of agriculture research. Following upon the Late Glacial Maximum, about 23 thousand years ago, as the earth's surface was gradually warming, the Younger Dryas event was an abrupt climate reversal to colder and drier conditions between 12.8 and 11.5 thousand years ago. The archaeological concern since has been to identify in West Asia the cultural periods and hunter-gatherer-forager subsistence alterations that coincided with the abrupt alterations in environmental conditions during the Younger Dryas event. How did forager societies in West Asia adapt to the Younger Dryas event, its onset, and its abrupt terminus? Here, Bar-Yosef, Bar-Matthews and Ayalon review and synthesize the West Asian archaeological data for early plant cultivation and, as well, the synchronous data for the cold and possibly dry Younger Dryas event that is available from the speleothem record at Soreq Cave, Israel.

During the Late Glacial Maximum, ca. 23,000 to 18,000 years ago, forager groups spread across the Levant. This was a generally humid period with a short dry spell represented at the Ohalo II site, which was founded ca. 19,400 years ago when Sea of Galilee lake levels fell. The earliest plant cultivation at Ohalo II, well preserved due to the settlement's burning and subsequent submersion, was undertaken for a brief time (Weiss 2009). The termination of the dry period possibly marked the end of the cultivation experiment. In any case, subsequent attempts with plant cultivation are not documented until the late Younger Dryas event.

Bar-Yosef, Bar-Matthews and Ayalon understand the Younger Dryas event as a period of "changing and unstable environmental circumstances" during which "demographic pressure created by large numbers of forager groups caused regional upheaval, competition for resources, and local migrations from more arid areas . . . into the sown land"—that is, the western flank of the "big bend" in the central Euphrates River. Several early cultivation sites are now known from this region, making for an unusual density that is probably only in part due to the amount of archaeological research in that area. Adding interest and complication to the Younger Dryas event's adaptive effects are the now contradictory analyses of Younger Dryas period precipitation in the Levant. Soreq Cave speleothem analyses set the initial standard for understanding reduced precipitation during the Younger Dryas (Orland et al. 2012). The following year, however, analyses of Dead Sea rock varnish seemed to indicate a wetter Younger Dryas period (Liu, Broecker, & Stein 2013). New high-resolution proxy records from Lake Van, Turkey, definitive for Anatolia, the northern Levant, and northern Mesopotamia, indicate rapid increase of arid desert-steppe plants in the pollen assemblages and a dramatic drought signature peak in the stable oxygen isotope record for the Younger Dryas period (Pickarski et al. 2015). More recently, Hartman and colleagues (2016) suggest that gazelle tooth enamel indicates consumption of humid grasses during the cold Younger Dryas while Cheng and colleagues (2015) observe little Younger Dryas climate change at Jeita Cave. How these sets of contradictory data will shake out is unknown, but one discovery remains: at least twelve years of intense drought occurred at the end of the Younger Dryas event, as recorded in Soreq Cave (Orland et al. 2012).

The Bar-Yosef, Bar-Matthews, and Ayalon hypotheses are realistic assessments of both the Younger Dryas event's effects upon the fully occupied forager landscape and the archaeological data supporting an early shift to cereal cultivation in the Levant. Of course we need additional tests of the demographic pressure and landscape packing estimated by Munro (2009) and utilized here, along with still higher resolution synchronisms between the archaeological and paleoclimate data. Nevertheless, "regional upheaval, competition for resources, and local migrations" in the wake of the Younger Dryas event reside at the foundations of human behavioral ecology models for the origins of agriculture (Gremillion, Barton, & Piperno 2014).

Abrupt Climate Change and the Spread of Farming to Europe 8600-8000 Years Ago

The earliest Holocene abrupt climate change occurred between ca. 8.6 and 8.0 ka cal BP, a more than 500-year long period of extreme cold that is documented globally. Weninger and Clare explain that the onset of this event is synchronous with the long-distance movement of the earliest farming communities from West Asia into the Aegean. Further, they demonstrate that the end of this cold period is synchronous with the further spread of early farmers out of the Aegean at around 8.2 ka cal BP. Thereafter, it took only about a century for farming to be adopted throughout Southeast Europe. Weninger and Clare treat the chronology and distribution of this megadrought event in full and stress that it manifested as two superimposed events in West Asia and Europe. The first was the Siberian High, a period of intensely cold and fast-flowing air masses that intruded into West Asia beginning about 8600 years ago (8.6 ka BP) and within which a briefer and higher magnitude occurrence, the 8.2 ka BP event proper, appeared about 8200–8000 years ago (van der Pflicht et al. 2011).

The 8.2 ka BP was pan-global in extent, with a strong signature in Europe, the Mediterranean, West Asia, and China. In West Asia, particularly prominent 8.2 ka BP records are available from Soreq Cave (Bar Matthews et al. 1999) and the Dead Sea (Litt et al. 2012; Migowski et al. 2006) and present a remarkable depositional hiatus at about 8000 years ago. In central Anatolia, Nar Gölü (Dean et al. 2015) provides a new lake sediment record for the event. Although its magnitude in a variety of proxies is relatively minor compared to the Younger Dryas event in Europe and West Asia, the 8.2 ka BP event is the highest magnitude abrupt climate change of the Holocene in most globally distributed records (Walker et al. 2012).

Considering these drought events, and establishing the synchronism between archaeological events and processes and the abrupt climate changes, Weninger and Clare define two fundamental understandings for the spread of farming, or neolithization, of West Asia and Europe. The first process, coincident with the 8.6 cal BP event, was the arrival of the first settlements to the Turkish lakes district, the western coast of Turkey, the Turkish Aegean, and the coastal Levant. This was a migration to milder climate regions during the Siberian High cold spell. The second set of adaptations, coincident with the 8.2 cal BP event, was a regional site abandonment labeled the "Yarmoukian crisis." During this period the highlands of Jordan and the Jordan Valley were abandoned, with resettlements restricted to lower lying and moister areas, and was followed by swift neolithization movements from the Aegean coast to northeastern Hungary.

Two recent reviews of archaeological and paleoclimate data for the 8.2 cal BP event dismiss this synchrony of 8.2 cal BP abrupt climate change and adaptive societal collapse responses in West Asia. Researchers at Sabi Abyad, in the Balikh Valley of northern Syria, believe the site was occupied continuously during this period and consider the continuity to be major evidence for the adaptive capabilities and resilience of early Neolithic village farmers (van der Pflicht et al. 2011). In fact the village occupation on one flank of the site (A) was abandoned at 8.2 cal BP and, possibly 50 to 100 years later, a new village (B) grew on the opposite flank of the site—a scenario similar to that at Çatalhüyük discussed by Clare and Weninger. The hiatus between the Sabi Abyad occupations is accommodated within standard deviations in their radiocarbon ages, which are confused with occupational durations. Indeed, the entire radiocarbon date analysis from Sabi Abyad has been deemed useless (Bayliss 2015). There are, additionally, no data from Sabi Abyad for cumulative site-size alterations, nor for regional settlement and alterations, which would be the anticipated expression of regional adaptations to reduced precipitation, colder temperatures, and reduced agricultural production. Rather, much site data points to adaptive responses to altered subsistence conditions at its radically new village: the expansion of tholoi residences, the introduction of a large mobile pastoralist population, a decrease in pig herding, an increase in sheep and goat for milk and fiber, and a sudden increase in clay sealings as personal property markers (van der Pflicht et al. 2011: 231). These fundamental agricultural and social alterations are attributed, in part, to the coincidence of the 8.2 cal BP event and the changed climatic and environmental conditions. That is, they were adaptations to the 8.2 cal BP event. Other forces that may have conditioned these alterations and adaptations are not mentioned and, indeed, might be difficult to observe, if they existed. Hence it is not altogether clear if the demise of village A represents that society's collapse and if the rise of the new village B represents post-collapse adaptations by relocation to a new 8.2 cal BP environment. Or, are these distinctions only a matter of semantics?

Another group of researchers (Flohr et al. 2016), find little chronological synchronism between the 8.2 cal BP event and major disruptions of this period, the abandonment of some settlements, and the neolithization-migration or habitat tracking that is detailed by Weninger and Clare. However, Flohr and her colleagues focus only on the brief 200-year period of the 8.2 ka BP event, which is possibly difficult to isolate in many archaeological records, whereas Weninger and Clare analyze the superimposed abrupt climate changes 8.6–8.0 cal BP. Lastly, it should be noted that a careful recent study documents regional abandonment in Scotland as a response not only to the magnitude of the 8.2 cal BP event's impact on climate change but also its abruptness (Wicks & Mithen 2014).

Megadrought and Imperial Collapse in Mesopotamia: 2200–1900 BC

The pan-global Holocene abrupt climate change event ca. 4200 years ago (4.2 ka BP), a megadrought that extended from ca. 2200–1900 BC, has prompted controversy among archaeologists as its pattern of coincident and synchronous societal collapses rewrites the archaeology of regions extending from the western Mediterranean to the Aegean to the Near East, the Indus, and beyond to Africa, China, and even north America. This global abrupt climate change event occurred in historical time in Mesopotamia, coincident with the collapse of the Akkadian Empire, and therefore challenges the traditional, text-based historiography of Mesopotamia's earliest empire and its successor states.

The 4.2 ka BP megadrought brought a 30–50 percent reduction in precipitation and cooling across the Mediterranean, west to east (with coincident heavy rains in Alpine Europe: Zanchetta et al. 2016), and across West Asia, Central Asia, and eastern Asia, Africa, and the western hemisphere, as expressed in marine, lake, speleoethem, glacial core, and tree-ring records. Intriguingly, there is yet no consensus explanation for this geological event with global expression, although various region-wide explanations, such as solar insolation variability Magny et al. 2013; Staubwasser et al. 2003), onset of El Niño conditions (Fisher 2011), and Atlantic Oscillation displacement (Booth et al. 2005), have been hypothesized.

The event is linked temporally, spatially, and causally with the regional settlement abandonments and political collapses of the Akkadian Empire (Weiss et al. 2012), the Old Kingdom in Egypt (Marshall et al. 2011; Revel et al. 2014; Welc et al. 2014), Early Bronze Age IV Levantine (Harrison 2012), and Early Bronze Age III Anatolian (Massa & Şahoğlu 2015) and Aegean societies (Davis 2013), Languedoc Late Neolithic and Rhône Valley Bell-Beaker societies in southern France (Carozza et al. 2015), and the Harappan-period cities of the Indus Valley (Ponton 2012). The chronological linkages across these regions are now exceptionally tight. One important example is the AMS (accelerator mass spectrometry) radiocarbon-dating synchronism at 2200 BC for the Leilan IIc Akkadian imperial collapse in northern Mesopotamia and the beginning of the First Intermediate Period in Egypt (Ramsey et al. 2010; Weiss et al. 2012).

Before its global expression was known, and before its abruptness, magnitude, and duration had been defined, if only approximately, the case for the 4.2 ka BP megadrought and linked dry-farming collapses and habitat tracking was sometimes criticized as a "climate determinism" argument that erroneously imputed causal force to climate change while ignoring the social forces that must have been involved in, for example, the Akkadian or Old Kingdom collapses. These were extensions of an older argument noted above (Butzer 1982), that if Nile River flow failed it was not a determinant of Old or New Kingdom Egyptian collapse, but must have been only one of several synchronous negative forces (political, social, and economic concatenations). Presumed here is a still older argument that only collections of forces have large social effects—an earlier 20th century position that is maintained by some to this day (Costanza et al. 2007). For the most part, such arguments dissolve against the highly resolved dating of the megadrought, its abruptness, and magnitude, and its synchronism with transregional societal collapses, regional abandonments and habitat tracking. Butzer (2012), for example, misdates the Akkadian collapse by a century or more, misses its synchronism with the First Intermediate Period in Egypt, and rejects the paleoclimate proxies for both Mediterranean westerlies and Nile River flow diminution. Similarly illuminating is the counterfactual question, "We know Nile flow failure occurred; would Egyptian collapse have occurred without Nile flow failure?" The problem of weighing causes, and types of causes (Cartwright 1999: 119), is a large social science problem to which the 4.2–3.9 ka BP event and its multiple hemispheric collapses draw attention.

The Late Bronze Age Collapse: Thirteenth to Eleventh Centuries BC

One of the great mysteries of Near Eastern and Mediterranean archaeology, and the subject of countless articles and monographs, including bestsellers (Cline 2014), is the crisis and collapse of the Late Bronze Age societies of the eastern Mediterranean and the Near East between ca. 1250–1100 BC, and the "dark age" and birth of the Early Iron Age societies that immediately followed. The drama of this process is uniquely recorded in Egyptian bas-reliefs and inscriptions and in Ugaritic and Hittite inscriptions, and focused in part upon a series of famines in West Asia, the Levant, and Egypt and the invasions of the "Sea Peoples" from coastal southeastern Europe. Recorded as groups with strange non-Semitic, non-Egyptian names, some clearly derived from Aegean and Anatolian toponyms, they included the Peleshet (Philistines) of biblical record who settled in these times upon the coast of Palestine, ready to greet the Israelites already entering the same land through the interstices of the region-wide Late Bronze Age collapses. The invasions by sea and land, with small ships and ox-drawn carts, resulted in the archaeologically visible destruction of many large and wealthy Late Bronze Age urban centers of the Levant and the blanket replacement of their cultures, with few surviving features, in the Early Iron Age (Killebrew & Lehmann, 2013).

Why were small bands of "Sea Peoples" able to topple the well-established and militarily powerful Late Bronze Age urban kingdoms of the Aegean and West Asia? Episodes of famine were already well known from the textual record for this period, but Kaniewski, van Campo, and colleagues were the first to situate and measure the hypothesized droughts within their definition of the independent paleoclimate record for the Aegean and the Levant in the thirteenth to tenth centuries BC (2013). The subsequent publication of a similar and confirmatory drought record (Langgut, Finkelstein, & Litt 2013), derived from the pollen analysis of a Lake Tiberias sediment core, showed the abrupt megadrought ca. 1250–1100 BC followed by an abrupt return of pre-drought humid conditions. Additional confirmatory data for the megadrought in the Levant derive from two new Dead Sea cores (Neugebauer et al. 2015). A new speleothem record from the Peloponnese, Greece (Boyd 2015), adds to the previously retrieved and coincident records of Aegean drought.

A recent critique of the data for late Bronze Age megadrought focuses upon the limited number of lake sediment core radiocarbon dates deployed to prove sub-decadal coincidence with the Late Bronze Age collapse (Knapp & Manning 2016). The authors conclude, however, that cumulative evidence for the aridification period, including its radiocarbon dating, is now essentially incontrovertible.

The "Sea Peoples" invasions and successes, however, require further description and explanation, as all agree. Can we develop a high-resolution chronology of drought and habitat tracking from southeastern Europe to the Levant and the Hittite Empire's Anatolian domains that explains the Sea Peoples' migrations and invasions and the sequences of drought and famine (Kaniewski, Guiot, & van Campo 2015)? Synchronous disruption of the Mediterranean westerlies, the driver of precipitation for the eastern Mediterranean, is visible in the paleoclimate records for the North Atlantic Oscillation and confirms the Aegean, Levantine, and Anatolian proxy records (Geirsdóttir et al. 2013; Blair, Geirsdóttir, & Miller 2015; Olsen, Anderson, & Knudsen 2012). The variability within and across these varied proxy records will be essential for articulating and explaining the dramatic historical details of the Late Bronze Age collapses across the Mediterranean and West Asian worlds. Similarly, we can now require archaeological definitions and explanations for the cultural and environmental impacts and adaptations of the successor Iron Age civilizations, and the "new opportunities" created for post-collapse reorganization. Impressively, the examination of the Philistine impact on southern Levantine floral ecosystems has already been initiated (Frumin et al. 2015).

The Basin of Mexico Megadrought and Teotihuacan Collapse: Eighth Century AD

The largest city in the pre-Hispanic New World, covering twenty-one square kilometers, was Teotihuacan, in the Basin of Mexico, with a population estimated at 125,000 sustained by spring-fed irrigation agriculture. At its height, in the sixth century AD, Teotihuacan was the center of a civilization whose economic, political, and artistic influence extended to the Yucatan and to the US Southwest (Millon 1970; Sanders, Parsons, & Santley 1979; Cowgill 2015). The great city flourished for about seven centuries, which in itself poses an archeological challenge, until its mysterious demise ca. 600–800 AD. Numerous studies have been dedicated to the dates of abandonment of the city's public buildings, The Great Fire, signs of internal struggle, and the distribution and dates of various socially significant artifact categories. Virtually all manner of endogenous and exogenous forces have been invoked and explored as causes for the abandonment of the city, including regional deforestation and soil erosion (Manzanilla 2003; Sanders, Parsons, & Santley 1979), but abrupt megadrought was only documented by Lachniet and colleagues in a breakthrough paper in 2012.

In this volume, Lachniet and Bernal revisit the data from the 2400-year stalagmite record from Juxtlahuaca Cave, which they have dated ultra-precisely, with uncertainties of less than about ten years. The results of their analysis document Basin of Mexico abrupt rainfall variations switching from wet to dry within ten to thirty years, and 30–50 percent precipitation reductions during a century-long drought centered on AD 750 that was coincident with the collapse of the city. Specifically, the peak dry conditions in their high-resolution rainfall reconstruction coincide with earlier proposed dates for the city's population decrease in the seventh or eighth centuries AD (Cowgill 1997).

Lachniet and Bernal underscore the coincidence of the city's rise, as well, with a period of above average precipitation and likely, therefore, higher agricultural productivity. Hence the rise and fall of the city were coincident with variant and measurable natural conditions for social exploitation and a natural force—megadrought—that proved insurmountable. The effects of megadrought upon the city's agricultural base only amplified, Lachniet and Bernal observe, the variety of consequent internal and violent frictions that may have accelerated the urban collapse and which now require archaeological reanalysis. It must be noted, as well, that the approximately two-century rate of the city's abandonment is a function of lengthy ceramic periodizations. This Teotihuacan abandonment period may shorten considerably when it is redefined by high-resolution radiocarbon dates.

Drought and the Classic Maya Collapse, AD 800–1100

The Maya abandonment and collapse of the Guatemalan lowlands and Yucatan highlands in the ninth century AD has been the most discussed societal collapse in the western hemisphere, famously, with virtually every possible cause discussed at length. A few researchers in the 1980s dared to suggest that drought may have been a cause, but it was not until the retrieval and analysis of the sediment core at Lake Chichancanab (Hoddell, Curtis, & Brenner 1995) that hard data were available to support this hypothesis (Gill 2001). Since then impressive progress has been made in the retrieval of additional paleoclimate proxy data, the highest resolution and most accurately dated now being the Yok Balum cave, southern Belize, speleothem analyses (Kennett et al. 2012).

In this volume, Kennett and Hodell review the precise Yok Balum stalagmite data and the archaeological data for the Maya collapse to derive several fundamental conclusions that revise previous attempts at Terminal Classic Maya climate and collapse synthesis. The Early Classic period (AD 440–640) was a period of anomalously high rainfall that was followed by a drying trend between AD 660 and 1000. Superimposed upon this drying trend were three severe and multi-decadal droughts. The first occurred between AD 820 and 870, the second around 930, and the third and most severe, between 1020 and 1100. According to Kennett and Hodell, the abrupt and severe megadroughts between 820 and 870 were "the unpredictable external shock" upon central and southern Maya lowlands already vulnerable to (1) agricultural failure from soil erosion caused by deforestation, and (2) political collapse due to high connectivity across regional sociopolitical nodes. In their view, the central and southern Maya lowlands settlements were more vulnerable to drought than "the less connected and therefore less vulnerable" northern lowlands settlements. The variability between the central region abrupt collapse and northern region gradual collapse, a subject of long-standing debate among Mayan archaeologists, was probably due to the differences in the regional political organization of settlements.

Additionally, it has been noted that the northern lowlands have over 6000 cenotes, steep-sided sinkholes fed by groundwater (Lucero 2006), while many settlements that survived the drought were also situated at fresh water refugia (Valdez & Scarborough 2014). Kennett and Hodell indicate, however, that the most severe drought had major consequences for the northern region settlements as well. To this day, indigenous Maya village agriculturalists continue to dwell in Mexico and Guatemala, of course, but the palace and temple dominated urban landscapes of pre-Hispanic Maya civilization never recovered from these megadrought episodes.

Here, as in other megadrought and collapse analyses, the effective causality is clouded by the absence of quantified or quantifiable relationships. Would Terminal Classic Mayan polities and agricultural production have been sustainable if they were not already, to some measure, soil-eroded field systems? Or was Terminal Classic megadrought, a 40 percent reduction in precipitation according to Medina-Elizade and Rohling (2012), insurmountable in all cases? The latter question remains open within other recent treatments of the Terminal Classic Maya megadroughts (Turner and Sabloff 2012; Webster 2014; Douglas et al. 2015, 2016).

The Tiwanaku Collapse at Lake Titicaca in the Thirteenth to Fourteenth Centuries AD

The collapse of the pre-Incan Tiwanaku Empire in the Andes is a classic example of megadrought-caused agricultural and political collapse, regional abandonment, and habitat tracking to refugia. For more than five hundred years, the Tiwanaku state prospered along the shores and the hinterland of Lake Titicaca with the products of intensive, flooded, raised-field agriculture. However, the onset of severe drought conditions in the thirteenth and fourteenth centuries AD reduced the level of Lake Titicaca by 12 meters, made raised field agriculture impossible, and diminished the subsistence of nucleated Tiwanaku settlement centers. The dissolution of Tiwanaku urbanism ensued, with dispersed populations moving into new, higher elevation refugia that afforded both water and defensive positions. In this volume, Kolata and Thompson note the tight synchronism between periods of Tiwanaku growth and collapse and a new higher resolution chronology for periods of high precipitation and drought, which is unambiguously expressed through archaeological settlement chronologies and the chronologies of two major adjacent paleoclimate proxy records, the Quelccaya glacial core and the Lake Titicaca sediment cores.

Without the intensive droughts of the thirteenth and fourteenth centuries, would the Tiwanaku state have survived? Kolata and Thompson note the gradual course of the Tiwanaku collapse beginning with earlier drought periods and continuing through to the mid-fifteenth century, as well as the existence of some early signs of social unrest, which suggest contributory collapse and resilience forces within the Tiwanaku social order. The "proximate cause" of the collapse, however, as noted early on, was located fundamentally within the megadrought's irremediable disruption of the highly adaptive Tiwanaku agricultural system (Ortloff & Kolata 1993; Dillehay & Kolata 2004). Tiwanaku social resilience to the megadrought was expressed as deurbanization, nomadization, and habitat tracking to sustainable high-elevation refugia.

Remarkably, within the framework created by Kolata and Thompson, a new genetic research project analyzing mitochondrial DNA samples is tracing population movements, migrations or habitat tracking, and the regional abandonments of megadrought stricken domains in the Andes at the time. The immigration of highland people to the coast at ca. AD 1150 generated rapidly increasing settlement density synchronous with the megadroughts in the southern Peruvian highlands. The pull force of increased precipitation in the lower valleys of the western Andean slopes was likely coincident with the push of Tiwanaku megadrought in the highlands (Fehren-Schmitz et al. 2014). The pan-Andean drought period, ca. AD 1250–1400, documented as well in recent lake sediment cores (Ledru et al. 2013), remains a key for understanding other Late Intermediate Period problems extending even to the causes of Wari collapse and Inka imperial expansion (Tung et al. 2016).

The Great Drought and Ancestral Pueblo Collapse in the late Thirteenth Century AD

Tree-ring studies focused upon chronology were developed by A. E. Douglass in the early twentieth century for archaeological purposes in the American Southwest and subsequently led to discovery of the Great Drought coincident with the Ancestral Pueblo (Anasazi) abandonments (Douglass 1929, 1935, 1936). Dendroclimatology defining long-term moisture balance now provides highly resolved and essential drought and megadrought data for the past two millennia across both hemispheres (Stahle et al. 2007; Cook et al. 2010; Cook et al. 2015). In the US southwest, the 400-year period of overall elevated aridity from AD 900 to 1300 was punctuated by four very dry epochs, the megadroughts centered at 936, 1034, 1150, and 1253 (Cook et al. 2004). The last epoch includes the Great Drought that extended from 1276 to 1297 and may have contributed to the Ancestral Pueblo collapse and abandonment of the San

Juan River, including settlements supported by dry-farming maize agriculture at Mesa Verde.

Carla Van West's GIS analysis of the Ancestral Pueblo settlement and resources first led to the hypothesis that drought alone did not account for the total abandonment of the region, that thousands could have remained, and that cultural forces had to have played a role as well (Van West 1994; Kohler 2010; Kohler, Varien, & Wright 2010). Research attention was thus refocused on the endogenous cultural forces that could have—but apparently did not—permit some remnant population to sustain themselves in the Colorado basin during the Great Drought. Some population apparently fled to agriculture sustaining springs, but only briefly (Kohler et al. 2008). By AD 1300 the entire population had emigrated to northern Arizona, western New Mexico, and the watershed of the Rio Grande (Varien 2010).

In this volume, David Stahle and his colleagues undertake remeasurement of tree-ring specimens from living trees and archaeological wood at Mesa Verde, Colorado, from AD 480 to 2008 to derive high-resolution earlywood and latewood width chronologies and, thereby, separately reconstruct a cool and early warm-season mositure history of the Ancestral Pueblo settlement region. They augment their results with seasonal reconstructions from the Mancos River to the east of Mesa Verde and from El Malpais National Monument in northwestern New Mexico. The conclusions derived from their study reinforce several salient facts. First, the Great Drought of AD 1276–1297 was one of the worst episodes of cool and early warm-season drought in a millennium. Second, dual-season drought occurred earlier in the thirteenth century, as well as its end. Third, early warm-season moisture conditions were generally below average over the San Juan region during the entire thirteenth century.

The Great Drought remains as the major determinant of regional collapse and Ancestral Pueblo migration in the late thirteenth century (Axtell et al. 2002), while other push and pull forces have proven extremely hard to identify in the archaeological and historical records. Kinship and refuge expectations, both difficult to discern or quantify against the material correlates of drought and migration, are perhaps the only partially non-climatic cultural forces that might explain why all fled the Great Drought while some thousands could have remained (Glowacki 2010; Berry & Benson 2010). A striking complement to the well-developed analyses of Ancestral Pueblo collapse and migration at the Great Drought is a new observation of immediate habitat tracking to refugia, such as the Pajarito Plateau, north central New Mexico (Bocinsky & Kohler 2014).

Flooding, Megadroughts, and the Collapse of Angkor in the Fourteenth Century AD

In the twelfth and thirteenth centuries AD, the Khmer capital at Angkor was a low-density megacity of about 750,000 persons spread over 1,000 square kilometers. Radiating from a center of massive public structures, temples, and water reservoirs (*baray*) was a vast city of residential structures grouped around their own temples, *baray,* and rice fields. Especially noteworthy (and described in this volume by Roland Fletcher et al.) was the city's elaborate water management system, an infrastructure that might have protected at least the elite from drought but that, ultimately, succumbed to monsoon flooding. By the fourteenth century most of Angkor was abandoned, and large areas of the surrounding plain had been converted to rice fields.

How and why this collapse occurred has largely been resolved through four closely coincident research projects. The Greater Angkor Project, a French, Australian, and Cambodian project from 2004–2009, alongside the Khmer Archaeology LiDAR Consortium, undertook GIS and LiDAR mapping of the city based upon earlier French ground mapping, along with selected excavations of crucial reservoir constructions and collapses (Evans et al. 2007, 2013). Edward Cook, meanwhile, directed the Monsoon Asia Drought Atlas collection of tree rings from more than 300 sites across the forested areas of Monsoon Asia and developed the annual dating and intensity of four historical droughts that had momentously affected the region (Cook et al. 2010). Brendan Buckley cored rare cypress trees in Vietnam, deriving a 759-year early monsoon drought index, that defined Angor Droughts I and II in the fourteenth and fifteenth centuries (Buckley 2010). Lastly, Mary Beth Day and colleagues (2012) retrieved lake sediment cores for the West Baray reservoir at Angkor that tracked reservoir drought, flooding, and channel failure in the fourteenth and fifteenth centuries.

The results from these teams of researchers are a detailed and complex history of intense megadrought during Angkor Drought I (AD 1345–1365) and II (AD 1401–1425), followed by intense flooding. The megadroughts reduced the megacity's agricultural rice production to unsustainable levels. The intense flooding destroyed essential reservoirs and channel structures. Essentially, the entire agro-production system was overwhelmed and failed. Political elites, alongside residential and agricultural worker populations, abandoned the dysfunctioning megacity and moved to Phnom Penh. Ancillary historical forces surrounded the droughts and floodings, but only reinforced the inevitable collapse.

Conclusions

Taken together, the nine essays in this volume challenge views that societal collapse is only a function of multiple social and environmental causes operating in concert, only a function of mistaken human decision-making, and only an underestimation of long-enduring civilizations and their traditions. The evidence suggests that abrupt megadroughts engendered agricultural and social conditions that could not be surmounted with agricultural or social innovations. Rather, societies adapted to these megadroughts with political collapse, regional abandonment, and population migration. Lesser climate changes—more gradual, lower in magnitude, shorter in duration—have not caused societal collapse, and modest, (if any) adaptive responses might well have defeated the instabilities caused by limited or short-term drought or colder temperatures. It is a challenging task, for instance, to locate adaptive societal responses to western Europe's gradual, half-a-degree centigrade temperature drop during the seventeenth century AD and the Little Ice Age (de Vries 1980; Parker 2014).

The analysis and study of the abrupt megadroughts of the Holocene provides several significant historical insights for the past, the present, and the future. First, the megadroughts and their societal impacts contribute to a dismantling of the historiographic view of conscious self-determinism, an intellectual tide that has been rising since the mid-nineteenth century in both the geological and social sciences. Second, data on the persistence and periodicity of Holocene megadroughts can yield geological insights into the current drought history of some regions, such as North America (Cook et al. 2014). Third, as already noted (Weiss & Bradley 2001), each of these preindustrial abrupt climate changes was a major and unanticipated natural event and thereby highlights, by contrast, contemporary climate change, which is anthropogenic, subject to societal decision-making, and an entirely new global phenomenon.

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