VOLUME 24 · NO 2 · DECEMBER 2016

PAST GLOBAL CHANGES

MAGAZINE

CLIMATE CHANGE AND CULTURAL EVOLUTION

EDITORS

Claudio Latorre, Janet Wilmshurst and Lucien von Gunten

News

PAGES 5th OSM and 3rd YSM

Excitement is building for PAGES' flagship event, the Open Science Meeting and associated Young Scientists Meeting, in Zaragoza, Spain, in 2017.
The YSM runs from 7-9 May. Over 80 participants have been selected.
The OSM runs from 9-13 May. More than 30 sessions have been proposed. Abstract submissions close 20 December 2016. Early registration closes 20 February 2017 and all online registrations must be submitted by 20 April 2017.
Read more and register: http://pages-osm.org
The social media hashtag for both events is #PAGES17.

DOI numbers now in PAGES Magazine

Have you noticed? All PAGES Magazines and associated articles from this issue forward will be assigned digital object identifier (DOI) numbers. DOI numbers provide a permanent link to the article location on the internet. Approximately 133 million DOIs have been assigned through a federation of Registration Agencies world-wide with an annual growth rate of 16% (Source: https://www.doi.org/faq.html).

Plan for new data standards

Paleoclimatology is a data-driven science, so being able to share your data, or re-use your colleague's, is essential. Unfortunately, data standards are currently lacking - a study shows that searching and formatting data takes up to 80% of the time spent analyzing it. PAGES is pleased to collaborate on a grassroots effort to fix this and encourages your involvement. Read all about it and be involved!
http://pastglobalchanges.org/news/1585-paleo-data-stand-linkedearth

Guest scientists at PAGES IPO

Two visiting scientists, Drs. Erle Ellis and Andrew Sluyter, have been based in Bern over the past few months, collaborating together and working on their contributions to PAGES LandCover6k working group.
http://pastglobalchanges.org/my-pages/guest-scientists

PAGES at EGU 2017

The PAGES working groups C-PEAT, 2k Network and Floods have organized sessions at the European Geosciences Union General Assembly in Vienna, Austria, from 23-28 April 2017. All details can be found on the calendar entry:
http://pastglobalchanges.org/calendar/127-pages/1617-egu-2017

Apply for meeting support or suggest a new working group

Each year, PAGES supports many workshops around the world. We also have an open call for new working groups. The next deadline is 3 April 2017. Read more about workshop support here: http://pastglobalchanges.org/my-pages/meeting-support and working group proposals here: http://pastglobalchanges.org/ini/wg/new-wg-proposal

Paleo jobs on the PAGES website

Are you looking for a new student, postdoc, faculty or other paleo-related posting? The popular jobs section on our website is continuously updated.
http://pastglobalchanges.org/my-pages/paleo-jobs

Help us keep PAGES People Database up to date

Have you changed institutions or are you about to move? Please check if your details are current. http://pastglobalchanges.org/people/people-database/edit-your-profile If you have problems updating your details, we can help. Please contact pages@pages.unibe.ch

Upcoming issues of PAGES Magazine

The next issue of PAGES Magazine will be on biodiversity and guest edited by our SSC members Lindsey Gillson (lindsey.gillson@uct.ac.za) and Peter Gell (p.gell@federation.edu.au). Contact them or the PAGES office if you are interested in contributing.

If you wish to lead a special section of the magazine on a particular topic, contact the PAGES office or speak with one of our SSC members. http://pastglobalchanges.org/about/structure/scientific-steering-committee

Calendar

1st Forest Dynamics Workshop
21-24 March 2017 - Jutland, Denmark

TropPeat: Low-latitude peat ecosystems
26-28 March 2017 - Honolulu, USA

Resilience in Long-term Ecological Datasets
27-31 March 2017 - Bergen, Norway

Lessons from 1.5-2°C warmer world
4-7 April 2017 - Bern, Switzerland

Late Pliocene climate variability
19-24 April 2017 - Durham, UK

Proxy system modeling and data assimilation
29 May - 1 June 2017 - Louvain-la-Neuve, Belgium

www.pastglobalchanges.org/calendar

Featured products

2k Network

- Nerilie Abram et al. generated large media interest when they found the onset of industrial-era warming across the oceans and continents began earlier than originally thought (2016, *Nature* 536).
- David Nash et al. present an assessment of evidence for hydroclimatic variability across the African continent, spanning the last two millennia (2016, *Quat Sci Rev* 154).
- A 2k consortium, led by Julie Jones, analyzes recent trends in high-latitude Southern Hemisphere surface climate (2016, *Nat Clim Change* 6).

PALSEA2

- Global sea-level rise in the 20th century was extremely likely faster than during any of the 27 previous centuries (2016, *PNAS* 113).
- A glacial isostatic adjustment model was used to reinterpret tropical sea-level reconstructions from Barbados, the Sunda Shelf and Tahiti (2016, *Nat Geosci* 9).

Varves Working Group

The PAGES endorsed working group linked paleolimnological reconstructions of lake bottom-water oxygenation to changes in land use and climate over the past 300 years (2016, *PNAS* 113).

Products from PAGES-supported meetings

- "Managing bark beetle impacts on ecosystems and society: priority questions to motivate future research", written by Jesse Morris et al., is the outcome of a meeting in Santa Fe, USA, April 2015 (2016, *J Appl Ecol*).
- "Assessing recent trends in high-latitude Southern Hemisphere surface climate" came from an Antarctica and Southern Ocean climate variability workshop held in La Jolla, USA, March 2015 (2016, *Nat Clim Change* 6).

Cover

Pueblo Bonito: a marvel of prehistoric architecture in the Southwestern USA continues to inform human-environment interactions

Despite a marginal semi-arid environment, Chaco Canyon, New Mexico, was the center of a regionally integrated system that peaked in the 11th century. Ancient Puebloans built great houses, such as Pueblo Bonito, from local sandstone and hundreds of thousands of conifers carried from distant mountaintops. Photo: courtesy of Scott Haefner Photography (http://scotthaefner.com).

doi: 10.22498/pages.24.2.55

Climate change and cultural evolution across the world

Claudio Latorre[1,2], J.M. Wilmshurst[3,4] and L. von Gunten[5]

From megafauna hunters in Patagonia to the fantastic civilizations in Chaco canyon, the Maya or settlers of remote oceanic islands, this issue aims to highlight how social decisions in the face of environmental change had long-lasting consequences for the evolution and development of prehistoric societies. Many regions of the world have undergone climate change since their first occupation by humans, and understanding how people who settled these places chose to confront or adapt (or failed to adapt) may play a vital role in sustainable planning of our modern societies.

From demographic collapse to social complexity, cultural evolution is an incredibly broad and complex topic at the forefront of much archaeological and anthropological research today. By affecting the availability of food and water to human populations, environmental drivers are a key factor for understanding this process. It is, however, an oversimplification to state that environmental drivers, such as climate change, are directly responsible for cultural change. Although there are many examples in the literature of large civilizations that suffered some degree of collapse, to attribute these social changes solely on shifting climate states (drought and the Maya is one particularly cited example) ignores other complex processes associated with how human societies make decisions regarding resource constraints.

However, the effects of climate change on past (and indeed future) societies cannot be understated and there are often multiple feedbacks (Fig. 1). Case by case comparative studies can bring out commonalities across cultures, varying geographies and global climate shifts. Such is the spirit behind this issue of *Past Global Changes Magazine*. We have brought together a series of examples, from most of the major continents and several island groups, to try to understand the underlying processes of how climate and environmental change affected cultural evolution and social decisions. The contributions combine archaeological records with the vast amount of paleoecological and climate proxy information that is now available for many of these regions.

Some of the oldest interactions between humans and the environment discussed in this issue are from South America, the last continental landmass to be colonized by migrating humans at the end of the Pleistocene. One of the best examples for showcasing the complex nature of human-environment interactions is summed up by Maldonado et al. (p. 56), in which, despite inhabiting one of the driest deserts on earth, the early peopling of the Atacama involved a series of choices regarding their environment. Further south in Patagonia, Villavicencio (p. 58) shows how climate and humans clearly must have interacted through ecosystem change to explain the demise of the endemic megafauna at the southernmost tip of the continent.

The impact of extended and persistent drought reconstructed from paleorecords is a unifying theme for several of the contributions in this issue. Zerboni et al. (p. 60) show how the end of the African Humid period during the mid-Holocene brought about new forms of social complexity and societal resilience, and question if extreme oscillations in climate brought about the end of major regional civilizations. In contrast, Weiss (p. 62) shows that mega-droughts lasting several centuries at ca. 4 ka BP brought about synchronous collapse of the major civilizations that occupied the Middle East and Mesopotamia.

Much more contested, however, is the role of drought in bringing about major social change in the Americas. As shown by Beach et al. (p. 66), topography as much as climate may explain the diverse social responses to the onset of drought conditions towards the end of the "Classic" Maya period. Such a complex relationship may also explain the abandonment of the "great houses" of Chaco Canyon in New Mexico, USA, some 900 years ago during the Medieval Climate Anomaly. Betancourt and Guiterman (p. 64) provide us with an up-to-date review of the major aspects of this debate and stress that resource exhaustion and distribution problems may have played a pivotal role.

Oceanic islands were among the last areas to be occupied by prehistoric humans, who spread over the planet during the late Holocene. Rull et al. (p. 70) show that much still needs to be done to understand the waxing and waning of the Rapa Nui on Easter Island. Fernández-Palacios et al. (p. 68) highlight how recent human settlement over the last few thousand years has transformed the diverse Macaronesian island environments, but how they interacted with climates over this time is an area needing further research effort. Finally, Holz et al (p. 72) return to southern Patagonia to bring up the issue of how fire can be a critical parameter for assessing the impact of human-environment-climate interactions, especially in regions where naturally caused fires were infrequent.

AFFILIATIONS

[1]Departmento de Ecología & Centro UC del Desierto de Atacama, Pontificia Universidad Católica de Chile, Santiago, Chile
[2]Institute of Ecology & Biodiversity, Santiago, Chile
[3]Longterm Ecology Lab, Landcare Research, Lincoln, New Zealand
[4]School of Environment, The University of Auckland, New Zealand
[5]PAGES International Project Office, Bern, Switzerland

CONTACT

Claudio Latorre: clatorre@bio.puc.cl

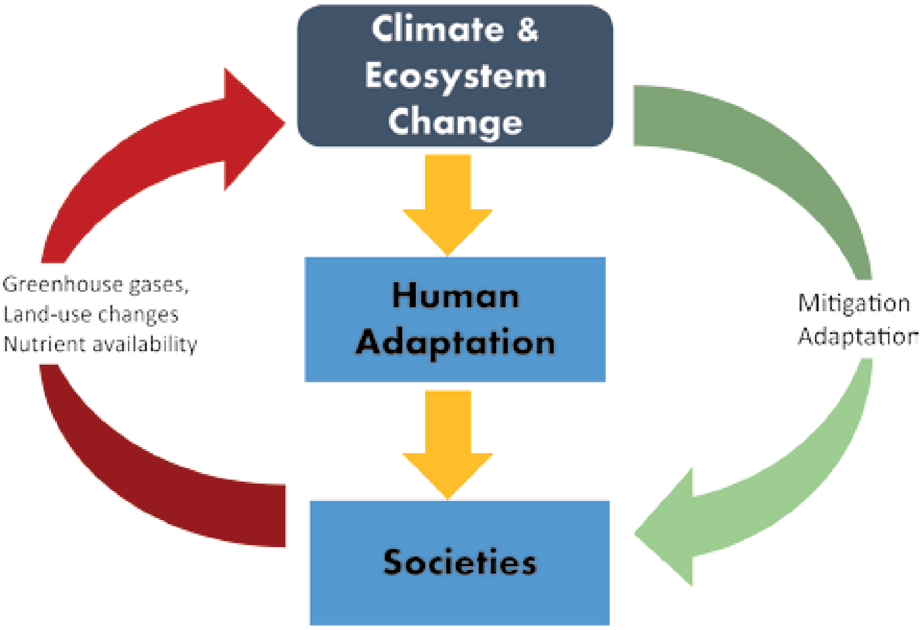

Figure 1: The relationship between humans and climate is complex and involves multiple feedback loops. As climate and ecosystems change over time, humans as organisms adapt to survive but as societies they can, in turn, influence the direction of future ecosystem change. This then feeds back into the decisions societies make to adapt to ongoing change as well as mitigation strategies.

doi: 10.22498/pages.24.2.56

Climate change and social complexity in the Atacama Desert during the Late Quaternary

Antonio Maldonado[1], C.M. Santoro[2] and Escallonia members[3]

Prehistoric human groups in the Atacama Desert developed socio-cultural complexities despite living in the world's driest desert. Different technological adaptations were developed as part of their interactions with variable environments over the last 14,000 years.

Human history can be understood as the constant mutual interaction between variable environments and social systems. It is the basis for many archaeological and socio-natural science studies worldwide and is particularly prominent in the Atacama Desert in northern Chile. Using an eco-anthropological perspective, we focus on identifying and explaining social continuities and discontinuities that occurred during key cycles of water availability since the first humans arrived, ca. 14 ka ago, at the Pampa del Tamarugal (PdT), in the hyperarid core of the Atacama Desert (Fig. 1). The major trends of long-term history of human-environment interactions show that people developed different ways of living, to endure the desert even during the driest climatic periods instead of completely abandoning it or, even worse, suffering cultural collapse.

The first peoples in Pampa del Tamarugal and Tarapacá region (14-10 ka BP)

Ecosystems and human societies in the Atacama Desert have been constrained mainly by the lack of water. The first human occupation occurred at the end of the Pleistocene, during relatively moist periods (at 17.5-14 and 13-10 ka BP; Quade et al. 2008). In the PdT, these humid periods increased perennial stream discharge and groundwater tables, expanding riparian and wetland ecosystems into what is now the hyperarid core of the desert (Gayo et al. 2012; Fig. 2). During those humid periods, the desert became an attractive habitat for hunter-gatherers, plenty of camelids (i.e. guanacos and vicuñas), rodents and birds. The archaeological evidence shows human occupations next to paleowetlands surrounded by trees (i.e. *Prosopis* species parkland), the dry trunks of which are still preserved and visible on the surface of the desert (Santoro et al. in press; Fig. 1). Diverse contemporaneous open camps, like QM12 (Fig. 1 and 2), show complex hunting-gathering systems successfully adjusted to the ecosystems in the PdT, coupled with long-distance human interaction from the Pacific coast and the high Andes.

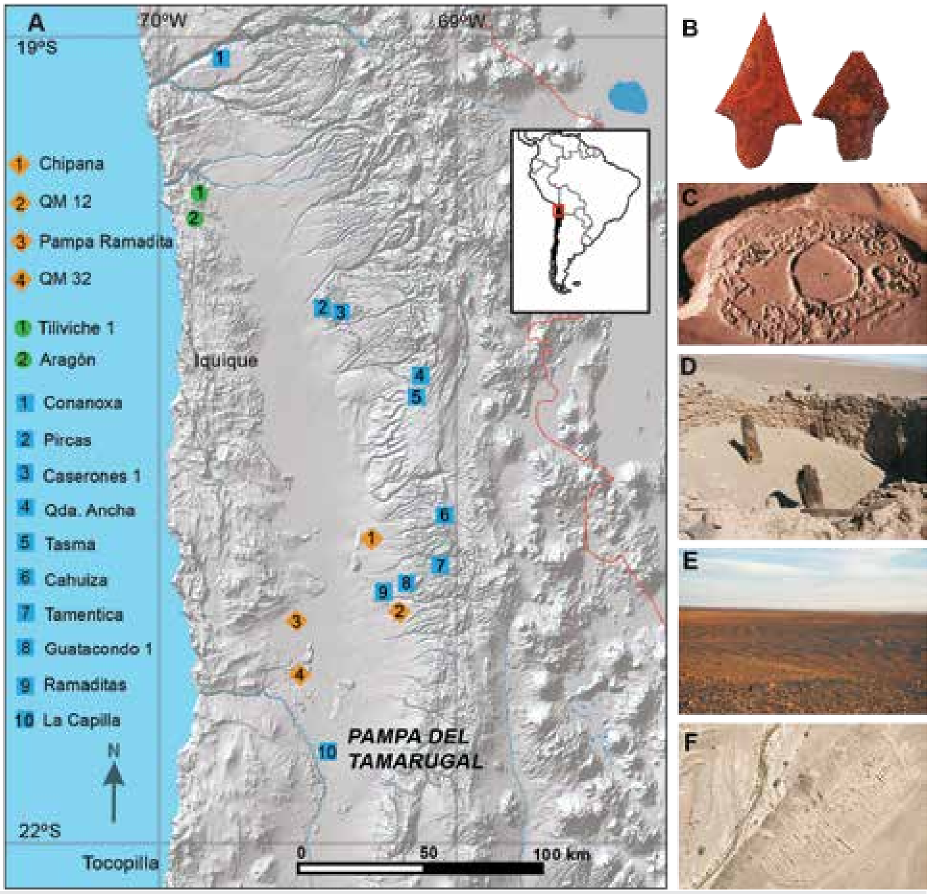

Figure 1: (A) Location of Early- (orange), Mid-Holocene (green) and Formative (blue) sites. **(B)** Late Pleistocene projectile points. **(C, D, F)** Formative villages. **(E)** Cropfields in Guatacondo. Red line shows today's border between Chile and Bolivia.

Environmental stress and socio-environmental discontinuity (10-3 ka BP)

The beginning of the Holocene (ca. 10 ka BP) seems to have triggered drastic transformations in settlement patterns and cultural behavior that lasted for several millennia due to the establishment of fluctuating arid conditions in the southern Atacama Desert (Núñez et al. 2013; Fig. 2). Archaeological data show a phenomenon of socio-environmental discontinuity that has been conceptualized as the "*silencio arqueológico*" (archaeological silence; Núñez et al. 2013).

Particularly in the PdT, the onset of hyperarid conditions triggered ecological stress characterized by the dramatic reduction of productivity in the ecosystem. Accordingly, people possibly migrated toward more productive areas such as the coast, where sequences of continuous occupation began approximately 9 ka BP, with complex ideological innovations, including artificial mummification (Marquet et al. 2012) and the development of a specialized technology focused on the exploitation of marine resources. More abundant settlements and the development of new technologies occurred along the coast since 7 ka BP (Castro et al. in press). The Altiplano, located eastwards of the PdT, was also productive as it may have been less vulnerable to climate change and maintained sustained environments (Ledru et al. 2013) and key locations for hunter-gatherers during the arid Mid-Holocene (Pintar 2014). Archaeological data

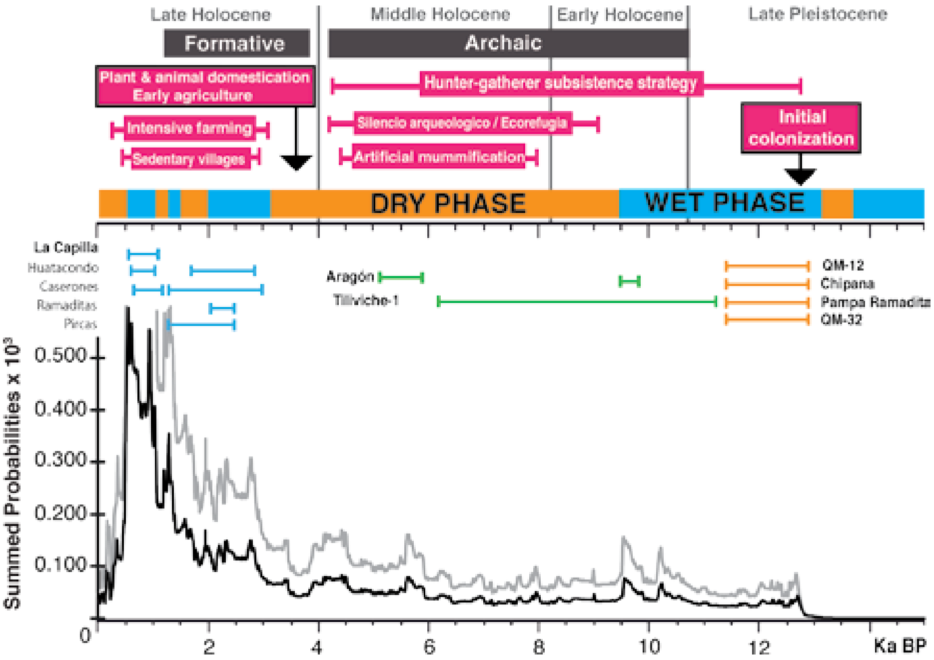

Figure 2: Paleoenvironmental and archaeological synthesis of the PdT since the Late Pleistocene showing human occupation modes, dry/wet phases, main archaeological sites (Fig. 1) occupation timing and occupation density (black line) measured through the summed probability ^{14}C ages from archaeological sites in the PdT. The grey line is a 2x exaggeration of the black line. Modified from Santoro et al. (2016).

show intensification in occupation after 10 ka BP. Other groups might have settled around local sources of permanent water within the PdT, or within narrow ravines such as Sapiga and Tiliviche canyons, whose archaeological sites (Aragón and Tiliviche 1; Fig. 1) point out that local ecosystems were complemented with protein from coastal resources (Santoro et al. in press).

Evidence from the central Atacama also shows, however, that populations rebounded after 6 ka BP, meaning that the Mid-Holocene may not have been as dry as thought (Gayo et al. 2015; see Fig. 2).

The return to the Pampa del Tamarugal (3-1 ka BP)

In the late-Holocene in the PdT, between 2.5-0.7 ka BP, arid conditions gradually gave way to wetter climates, peaking between 2-1 ka BP (Maldonado and Uribe 2015; Fig. 2). The wet phase is partly coeval with the cultural Formative period (2.5-1.5 ka BP), which is characterized by an intensification of social complexity and diversification of communities. Large, dispersed or concentrated villages with monumental public spaces were founded. A wide range of innovative technologies (i.e. ceramic, textile and metal production) and landscape arrangements were added to the traditional hunting-gathering systems. This involved sophisticated technologies for managing surface water including water dams, irrigation canals and farmland. These innovations generated a concentration of population and social power (Urbina et al. 2012; see Fig. 1a), coupled with an increase in population size (Gayo et al. 2015; see Fig. 2).

Internodal areas (1.0-0.5 ka BP) and capitalism (0.5 ka BP - present day)

Aridity, which increased from 1.0 to 0.7 ka BP and lasted until recent times, has been associated with sociopolitical turmoil and inequities (Uribe 2006). This resulted in massive population migrations to highland areas and the establishment of new and numerous settlements on the western slope of the Andes, since water resources in these areas were much more abundant and predictable (Maldonado and Uribe 2015; see Fig. 2). Consequently, new systems of agriculture (terraces and irrigation canals), strategic and defensive urban arrangements, and land management were developed. Increasingly circumscribed territories were managed by societies of "segmented" organizations (social groups independently organized). Thus, the PdT was transformed into an inter-nodal territory crossed by trains of llama caravans that connected the highlands with the coast.

During the Inca State regime (0.5-0.4 ka BP), the scale and organization of mining exploitation of copper and silver ore became important; thus, previous socio-economic systems were restructured for metal production (Zori and Tropper 2010). Traditional activities (i.e. agriculture, herding and foraging) gradually increased or intensified. The Spanish conquest (0.4-0.2 ka BP) brought new political, technological, demographic, and land-use conditions which changed the socio-environmental systems of the Atacama Desert. A proto-capitalist regime was introduced, focusing on the exploitation of raw materials, particularly minerals, which have dramatically stressed the human-environment relationships until today.

Discussion

The scale, intensity and continuity of human adaptive strategies in relation to fluctuating ecosystem resources have been diverse and variable throughout the last 14 ka BP in the Atacama Desert. Major humid or dry periods impacted the socio-environmental systems of hunter-gatherers, as well as the human occupation and the use of resources. Around 3 ka BP, a new, though less-intense, pulse of increased rainfall in the highlands reactivated ground- and surface-water flow in the hyperarid core of the Atacama. This boosted the development of complex water management technologies, and new social and ideological structures featured by the proliferation of people in the PdT. These innovations were also triggered by internal socio-cultural factors, which were capitalized by some communities in the PdT (e.g. Caserones village). The end of the wet period during the late Holocene (1.0-0.7 ka BP) led communities from the highlands and the coast to enlarge and improve novel systems of land use and management in the PdT. A new socio-political order dominated by segmented societies developed and lasted until the Inca epoch. This scenario was the base of the colonial and republican historical processes which accelerated the exploitation of desert environment resources. Both the environmental fluctuations and the people decisions based on cultural and social interests should be considered to explain the full range of complex sociopolitical variability in the PdT throughout the prehistory in the Atacama Desert.

ACKNOWLEDGEMENTS

CONICYT/PIA grant project ANILLO SOC1405.

AFFILIATIONS

[1]Centro de Estudios Avanzados en Zonas Áridas, Universidad de La Serena, Chile
[2]Instituto Alta Investigación, Universidad de Tarapacá, Arica, Chile
[3]M. Uribe, M.E. de Porras, J. Capriles, E.M. Gayó, D. Valenzuela, D. Angelo, C. Latorre, P.A. Marquet, A. Domic, V. McRostie, V. Castro

CONTACT

Antonio Maldonado: amaldonado@ceaza.cl

REFERENCES

Castro V et al. (in press) Chungara 48

Gayo EM et al. (2012) Earth Sci Rev 113: 120-140

Gayo EM et al. (2015) Quat Int 356: 4-14

Ledru MP et al. (2013) Holocene 23: 1545-1557

Maldonado A, Uribe M (2015) In: Retamal MS et al. (Eds) Actas del XIX Congreso Nacional de Arqueología Chilena. Sociedad Chilena de Arqueología, 193-200

Marquet PA et al. (2012) PNAS 109: 14754-14760

Núñez L et al (2013) Quat Int 307: 5-13

Pintar E (2014) Chungara 46: 51-71

Quade J et al. (2008) Quat Res 69: 343-360

Santoro CM et al. (2016) In: Aldunate C et al. (Eds) Prehistoria en Chile desde sus Primeros Habitantes hasta los Incas. Editorial Universitaria, Santiago

Santoro CM et al. (in press) J Anthropol Archaeol, doi: 10.1016/j.jaa.2016.08.006

Urbina S et al. (2012) Bolet Museo Chile Arte Precolombino 17: 31-60

Uribe M (2006) In: Lechtman H (Ed) Esferas de Interacción Prehistóricas y Fronteras Nacionales Modernas: Los Andes Sur Centrales. Instituto de Estudios Peruanos e Institute of Andean Research, 449-502

Zori CM, Tropper P (2010) Bolet Museo Chile Precolombino 15: 65-87

doi: 10.22498/pages.24.2.58

Late Quaternary megafaunal extinctions in southern Patagonia and their relation to environmental changes and human impacts

Natalia A. Villavicencio

The chronology of megafaunal extinctions in southern Patagonia suggest that they are due to a combination of human impacts, and vegetation and climate changes. Most extinct megafauna coexisted with humans for a relatively long time, and died out at different times.

By the end of the Pleistocene, the world lost most of its large mammal species in what is known as the Late Quaternary extinction event (LQE; Martin and Klein 1984), the magnitude and timing of which differs among continents (Koch and Barnosky 2006). For more than five decades, the discussion about the possible causes of extinction has revolved around the human impacts caused by modern humans moving out of Africa, climate changes associated with the glacial-interglacial transition or combinations of both (Martin and Steadman 1999). South America was one of the most severely impacted continents, losing around 82% (53 genera) of all its large mammal species with average body mass exceeding 44 kg (Brook and Barnosky 2012). In South America, human arrival and late glacial climate changes occurred within a relatively short span of time, although marked regional differences are present in both the timing and direction of climate change. These regional differences provide opportunities to test possible synergistic effects of these changes in driving the LQE (Barnosky and Lindsey 2010).

The case of Southern Patagonia

Several decades of research in caves and rock shelters in the area of Última Esperanza, Tierra del Fuego and Pali Aike (Fig. 1) have resulted in rich collections of extinct megafauna and evidence of the earliest human inhabitants in the area. Particularly, intense work in the Cerro Benítez and Lago Sofía area has produced dozens of radiocarbon dates on extinct fauna and helped establish one of the most complete chronologies of megafaunal extinction available from South America. Villavicencio et al. (2016) reviewed radiocarbon chronologies of megafaunal extinction and of human occupation from Última Esperanza, and the timing of major changes in climate and vegetation. Their main conclusions were (Fig. 2): First, mega-carnivores (*Panthera* and *Smilodon*) disappear slightly before the extinction of most of the herbivores, contrary to what is expected in a situation of trophic collapse. Second, *Hippidion*, *Lama* cf. *owenii* and mylodontids apparently coexisted with humans for hundreds of years (*Hippidion* and *Lama* cf. *owenii*) to millennia (mylodontids), ruling out a scenario of rapid overkill of these taxa by humans. Finally, *Hippidion* and *Lama* cf. *owenii* disappeared when cold grasslands were replaced by *Nothofagus* forest, followed by mylodontids disappearance, which occurred when the forests finally dominated the landscape.

Megafaunal extinctions in Última Esperanza

Over 45 new radiocarbon dates on extinct megafauna in Última Esperanza were recently published (Metcalf et al. 2016; Martin et al. 2015), making an update of previous analyses possible by combining these new dates with the Villavicencio et al. (2016) dataset of 62 high-quality radiocarbon dates. In the combined dataset, best estimates of local extinction times were obtained using the Gaussian-resampled, inverse-weighted method (GRIWM) of McInerny et al. (described in Bradshaw et al. 2012).

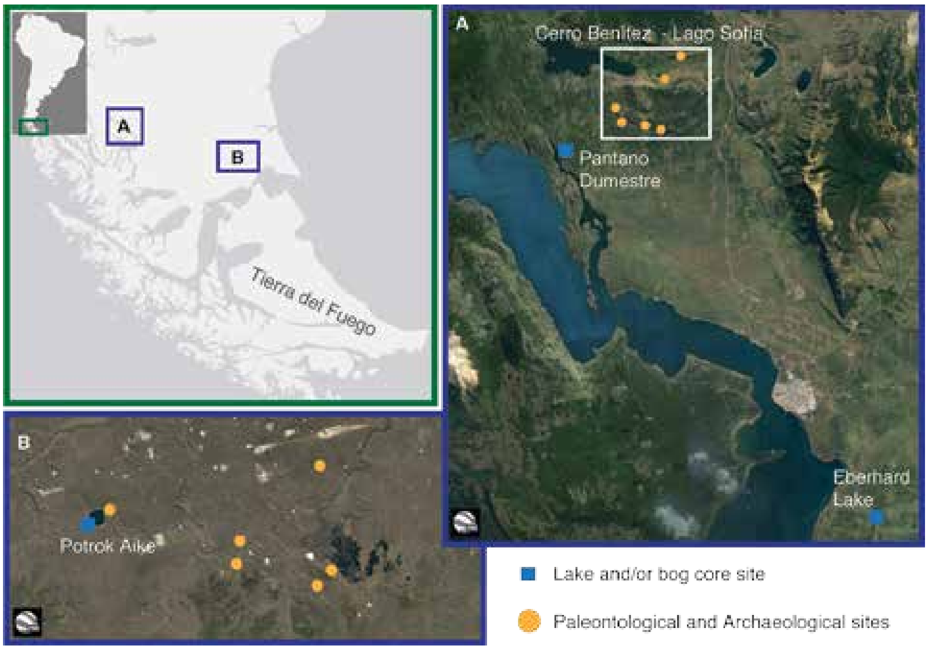

Figure 1: Map of southern Patagonia and location of study sites. **(A)** Última Esperanza, **(B)** Pali Aike.

When the new dates are added, the general patterns of extinction as inferred from the GRIWM best-estimates appear almost the same as those calculated from the original 62 dates (Fig. 2). The extinction of *Panthera* and *Hippidion* occurred earlier according to the new, combined dataset than according to the initial one. *Lama gracilis*, which was previously known by a single radiocarbon date, now has a more resolved record showing possible coexistence with humans for 900 to 1,200 years. This taxon disappears from the record between 12.6-12.2 ka BP, when the landscape was still dominated by cold grasslands. Four out of the eight taxa shown in Figure 2 become locally extinct during the warming phase following the Antarctic Cold Reversal cooling period recorded in the Antarctic EPICA Dome C ice core. *Mylodon*, and possibly *Hippidion*, disappear later from the record, between 12-10 ka BP.

Current archaeological evidence is scant and the number of dated human occupation events implies that Última Esperanza was visited on an ephemeral basis (Martin and Borrero, in press). However, the pattern of extinction remains evident, even after adding new radiocarbon dates to the analysis, and does not rule out the possibility of humans playing a role in driving some of these extinctions. Competition with humans could explain the disappearance of the large felids from the area between 700 and 2,000 years BP before some of the largest herbivores went extinct, as was proposed in Villavicencio et al. 2016. On the other hand, slow attrition of megaherbivores by human hunting, coupled with vegetation change, could also explain the later disappearance of mylodontids, horses and some of the extinct camels. Interestingly, human presence in the area fades at the same time of the last megafaunal extinction (*Mylodon*), reemerging more than 3000 years later.

Looking outside Última Esperanza: Pali Aike

Pali Aike is a volcanic field located east of Última Esperanza (Fig. 1). Archaeological research in the area dates back to 1936 (Bird 1988). Since then, numerous excavations have

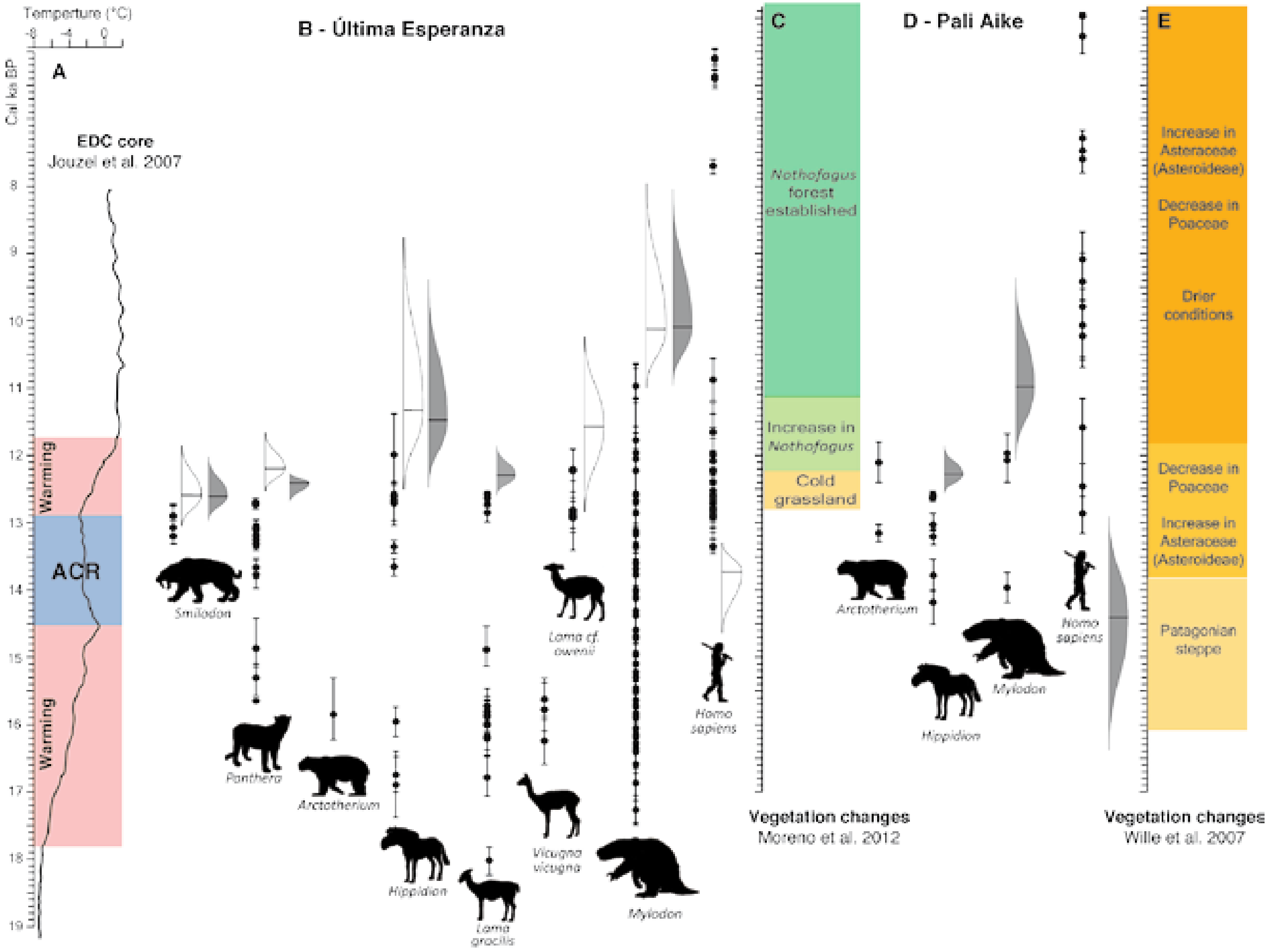

Figure 2: (A) Temperature record from the EPICA Dome C ice core, Antarctica. Blue bar: Antarctic Cold Reversal, red bars: warming events (Jouzel et al. 2007); **(B and D)** Chronology of megafaunal extinctions and human arrival in Última Esperanza (modified from Villavicencio et al. 2016) and Pali Aike; **(C and E)** Vegetation change estimations for Última Esperanza (Moreno et al. 2012) and Pali Aike (Wille et al. 2007). Black circles: direct calibrated (Calib 7.04; Stuvier and Reimer 2014) radiocarbon dates on extinct megafauna and human evidence. The GRIWM best-estimates of extinction timing (or timing of human arrival) are indicated by the unshaded (Villavicencio et al. 2016) and shaded (this work) normal distributions, with the 95% confidence band depicted by the areas around the mean (black line: most probable time of extinction).

revealed the presence of extinct megafauna and humans during the late Pleistocene-Holocene transition (Martin 2013). This area is an interesting example to compare with Última Esperanza since it shares some of the same extinct taxa (Fig. 2) and is located in the same region (225 km to the east), but differs in the characteristics of human occupation and in the nature of both present-day vegetation and past environmental changes. Archaeological evidence for Pali Aike suggests more permanent human occupation in the area beginning ~12.9 ka BP (Martin and Borrero, in press). According to pollen records, Pali Aike was a cold Patagonian steppe dominated by grasses during the late Pleistocene, but transformed into shrubbier, less grass-dominated landscape between 13.9-11.9 ka BP, which has been interpreted as evidence for drier conditions (Wille et al. 2007). Southern beech (*Nothofagus*) forests found to the west never reached the area.

The megafaunal extinction record is less robust, when compared to results from Última Esperanza, as it consists of only 10 dates for three extinct megamammals. As shown in Figure 2, extinct fauna coexisted with humans for time periods ranging between 300 to 3,500 years. In general, the intervals of coexistence were shorter compared to Última Esperanza, which would be consistent with more permanent human presence in this area exerting greater pressures on megafauna. Coexistence between humans and *Arctotherium* is observed here, which has not been reported for Última Esperanza so far.

Resembling the extinction chronology in Última Esperanza, all three radiocarbon-dated taxa at Pali Aike disappeared from the record during the second warming period, after the Antarctic Cold Reversal, at a time when the landscape was becoming increasingly drier as inferred from pollen records (Wille et al. 2007).

Final remarks

The inclusion of 45 recently published radiocarbon dates in the chronology of extinction of Última Esperanza confirms the previously described general patterns and shows that a combination of human impacts and vegetation changes seem likely as the key drivers of megafaunal extinctions. Pali Aike shows interesting similarities with Última Esperanza - nonetheless more work is required, especially more radiocarbon dates on megafauna, in order to develop more robust conclusions.

ACKNOWLEDGEMENTS

Thanks to Anthony D. Barnosky for insightful comments about this work.

AFFILIATION

Department of Integrative Biology and Museum of Paleontology, University of California, Berkeley, USA

CONTACT

Natalia A. Villavicencio: nvillavicencio@berkeley.edu

REFERENCES

Bird JB (1988) Travels and archaeology in South Chile. University of Iowa Press, 278 pp

Barnosky AD, Lindsey EL (2010) Quat Int 217: 10-29

Bradshaw CJA et al. (2012) Quat Sci Rev 33: 14-19

Brook BW, Barnosky AD (2012) In: Hannah L (Ed) Saving a million species: extinction risk from climate change. Island Press, 179-198

Jouzel J et al. (2007) Science 317: 793-796

Koch PL, Barnosky AD (2006) Ann Rev Ecol Evo Syst: 215-250

Martin PS, Klein RG (1989) Quaternary extinctions: a prehistoric revolution. University of Arizona Press, 892 pp

Martin PS, Steadman DW (1999) In: MacPhee RDE (Ed) Extinctions in near time. Springer, 17-50

Martin FM, Borrero LA (in press) Quat Int, doi: 10.1016/j.quaint.2015.06.023

Martin FM (2013) Tafonomía de la Transicion Pleistoceno-Holoceno en Fuego-Patagonia. Ediciones de la Universidad de Magallanes, 406 pp

Metcalf JL et al. (2016) Sci Adv 2, doi: 10.1126/sciadv.1501682

Moreno PI et al. (2012) Quat Sci Rev 41: 1-21

Stuiver M, Reimer PJ (2014) Calib 7.01 Radiocarbon Calibration

Villavicencio NA et al. (2016) Ecography 39: 125-140

Wille M et al. (2007) Rev Palaeobot Palyn 146: 234-246

doi: 10.22498/pages.24.2.60

The end of the Holocene Humid Period in the central Sahara and Thar deserts: societal collapses or new opportunities?

Andrea Zerboni[1], S. Biagetti[2,3,4], C. Lancelotti[2,3] and M. Madella[2,3,5]

The end of the Holocene Humid Period heavily impacted on human societies, prompting the development of new forms of social complexity and strategies for food security. Yearly climatic oscillations played a role in enhancing the resilience of past societies.

The Holocene Humid Period or Holocene Climatic Optimum (ca. 12–5 ka BP), in its local, monsoon-tuned variants of the African Humid Period (DeMenocal et al. 2000; Gasse 2000) and the period of strong Asian southwest (or summer) monsoon (Dixit et al. 2014), is one of the best-studied climatic phases of the Holocene. Yet the ensuing trend towards aridity, the surface processes shaping the present-day arid lands and the cultural responses to these are still debated. Human reactions to arid environmental conditions have been sometimes described in terms of demographic decrease (e.g. Manning and Timpson 2014) and as driving socio-cultural complexity (e.g. Kuper and Kröpelin 2006). These two concepts, although apparently conflicting, are not mutually exclusive. The onset of arid conditions can lead to demographic decrease or the rearrangement of the population around important or secure resources. In turn, this can favor the adoption of different strategies to cope with the new climatic conditions, leading to augmented social stratification and complexity, and eventually to the emergence of hierarchical state-like entities.

The transition toward aridity

The African Humid Period is regarded as the most favorable period for human settlement in northern Africa during the Holocene. It corresponds to the so-called Green Sahara, often seen as the apex of Saharan prehistoric civilizations. Its termination represents a crucial moment for past communities. Whether the African Humid Period ended abruptly (e.g. deMenocal et al. 2000) or gradually (Kröpelin et al. 2008) is still discussed. In the SW Fazzan of Libya (Fig. 1), its end (around 5.5 ka BP) determined the rapid decline of natural resources in the climatically sensitive dunes and lowland environments. On the other hand, along the main rivers, which were fed by large aquifers located within the massifs, seasonal water availability persisted for several millennia (Cremaschi and Zerboni 2009). Smaller rivers may have turned into ephemeral streams, or dried out rapidly, but major endorheic watercourses progressively switched into oases, seasonally reactivated by rainfall (Cremaschi et al. 2006). Coeval with North Africa, the Thar Desert (Fig. 1) desiccation began around 6 ka BP (Madella and Fuller 2006), as revealed by the Lake Lunkaransar sediment record, which after some fluctuations dried out by 5.5 ka BP (Enzel et al. 1999). Recent paleoclimatic records from Kotla Dahar, a lake located at the north-eastern edge of the distribution of Indus settlements (Haryana, India), show a general trend towards desertification and higher evapotranspiration between 5.8 and 4.2 ka BP, followed by an abrupt increase in $\delta^{18}O$ values and relative abundance of carbonates, indicative of a sudden decrease in Indian summer monsoon precipitations (Dixit et al. 2014).

Aridification and cultural processes

Given the diverse physiographic characteristics of the Sahara and the Thar deserts, the climate-driven changes of the landscape likely occurred with different tempi and magnitudes, thus variably affecting past human societies. In both areas, the reconstruction of mid- to late Holocene cultural trajectories is still affected by the patchiness of radiometric data, as well as the scarcity of field-based studies that consider both morpho-sedimentary and archaeological contexts across the region. Nonetheless, during the aridification phase, archaeological evidence in these areas points to continuity of occupation, but with changes in settlement pattern, rather than full-fledged abandonment.

In the SW Fazzan, the transition from the Late Pastoral (5-3.5 ka BP) to the Final Pastoral (3.5-2.7 ka BP) marks the ultimate adaptation to hyperarid conditions and, later, the rise of the Garamantian kingdom (2.7-1.5 ka BP; Mori et al. 2013). According to the most recent paleoclimatic reconstructions (Cremaschi and Zerboni 2009; see also Fig. 2), it seems that the initial phase of the Garamantian kingdom was characterized by a relatively humid environment, whereas the unification of the kingdom period coincided with a clear decrease in rainfall. The end of the Garamantian kingdom occurred a few centuries after the onset of current hyperarid conditions, and was followed by a new tribal population structure and relocation in the landscape (Mori et al. 2013). Therefore, no deterministic correlation between climate or ecological changes and societal collapse can be postulated.

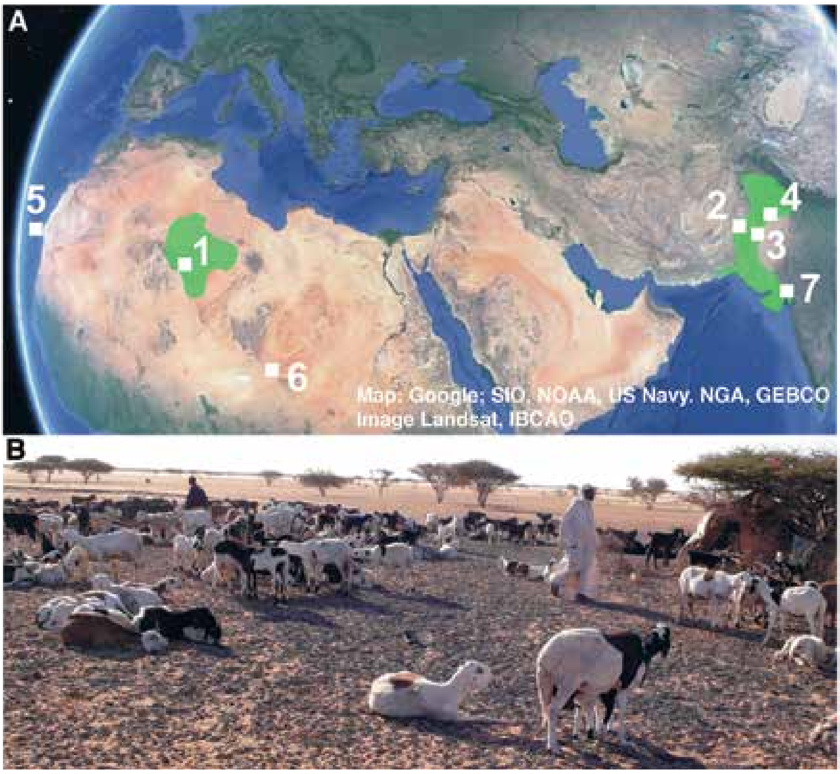

Figure 1: (A) Map with the areas (in green) mentioned in the text (central Sahara and Thar Desert; map: GoogleEarth™). Key: 1) Fazzan (Libya); 2) Thar Desert; 3) Lake Lunkaransar (India); 4) Kotla Dahar (India); 5) ODP Core 658C (off Mauritania); 6) Lake Yoa (Chad); 7) Lake Wadhwama (India). **(B)** In both regions, the study of subsistence strategies of resilient traditional societies is a tool to disclose the complexity of the responses of late Holocene archaeological communities to increased aridity.

In north-western South Asia, the beginning of the Harappan Civilization (Early Harappan) roughly coincides with the earliest phase of aridification (5.1 ka BP), and the urbanization period (Mature Harappan) develops in spite of the drying trend. Although the end of the Harappan Civilization has often been associated with extreme climatic events, the question is still under debate. A recent study suggests a possible correlation between the 4.1 ka BP drought event and the onset of the de-urbanization period, which started a couple of hundred years later (Dixit et al 2014). However, more than a collapse, the Late Harappan period (3.8-3.2 ka BP) seems to reflect settlement reorganization in consequence to hydroclimatic changes (Giosan et al 2012), with an increased number of small and more dispersed sites that occupied diverse ecological niches. The scale of hydroclimatic stresses probably decreased the resilience of Harappan society, but on its own does not provide a straightforward, deterministic explanation for the transformations in site size, distribution, and interrelationships across the whole area.

The role of an unsteady climate

Climate change has often been invoked as a reason for cultural change, yet human dynamics are not linearly related to climate change. Humans respond to what they perceive as changes in the landscape and in the available resources. Therefore, the transition to aridity in North Africa and north-west South Asia is better interpreted as the transition to a drier, yet oscillating, climate, with marked annual (or few-year lasting) variations in rainfall, and thus in of natural resources. This might have prompted the adoption of flexible and opportunistic strategies to cope with an unpredictable alternation of wet and dry years. Garamantian and Harappan state-like entities, although born and flourished in dry spells, might not have had the level of flexibility necessary to cope with high-frequency climatic variability and its erratic resource availability. The consolidation of centrally controlled socio-economical structures, including resource redistribution networks, resulted in a loss of resilience that ultimately led to a drastic change of the social organization.

The breakdown of these state-like structures, however, did not result in the abandonment of areas, but in the beginning of new socio-economic realities. Humans embraced new settlement strategies for the exploitation of residual and spotted natural resources. Local-scale choices and the accumulated ecological knowledge played a key role in the development of adaptive modes of landscape occupation and socio-cultural practice up to the present day. The oversimplified assumption of "aridity equal to abandonment" should be carefully reconsidered. In many past and current examples, people living in areas that experience aridity trends prefer to readjust and adapt their lifestyle to new conditions rather than abandon their land. How they adapt to new environmental conditions is one of the big issues of current archaeological research in arid lands. Due to the paucity of archaeological investigations directed toward past communities in the Sahara and the Thar deserts, much of the dynamics related to these adaptive strategies still evade our knowledge. Furthermore, in the areas discussed here, the scarcity of data for the post-Garamantian and, to a lesser extent, post-Harappan periods, prevents the construction of robust models describing demographic fluctuations during the late Holocene. Presumably (compared with present-day local adaptations), a more flexible and less-permanent settlement pattern occurred, featuring villages set around water sources (e.g. springs, oases, ephemeral streams). These villages were connected to more mobile, smaller groups adapted to exploit extremely arid areas. The (pre-)historical root of current adaptation to drylands is a key issue to refine our understanding of human dynamics in extreme environments.

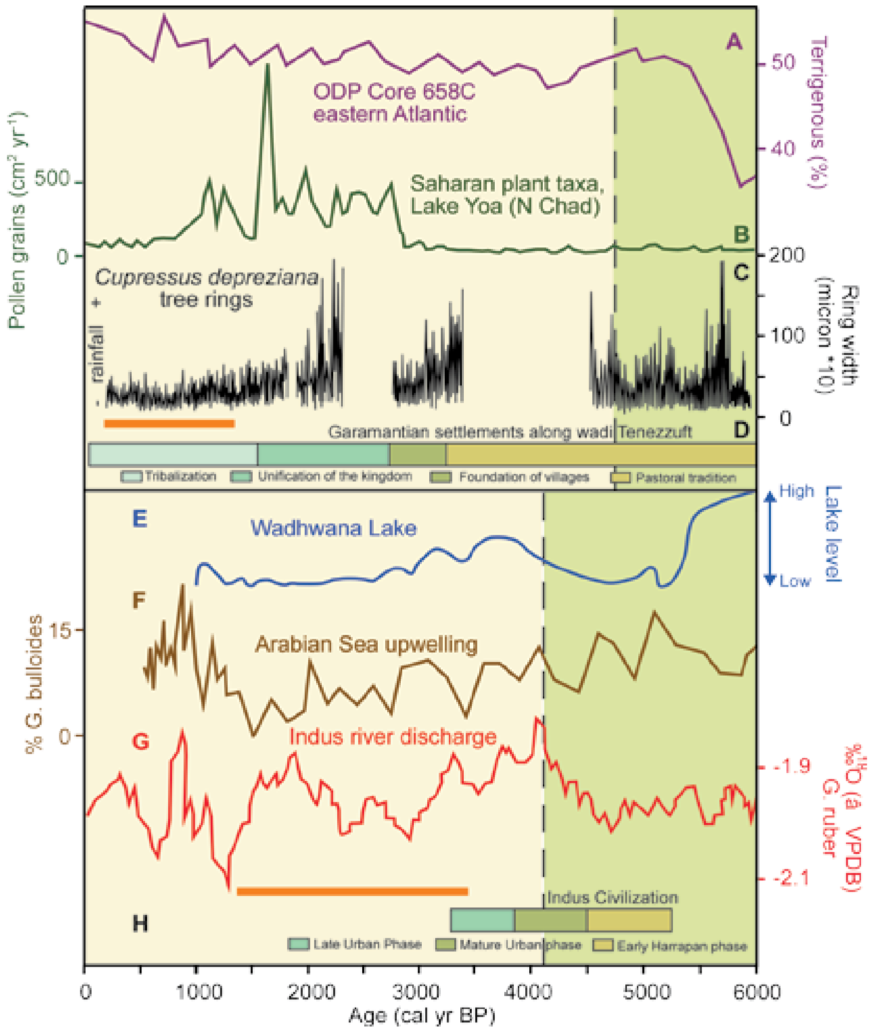

Figure 2: Correlation between climatic data and cultural evolution in the Central Sahara and the Thar Desert in the mid-late Holocene. The transition from green to yellow in the background corresponds to the transition toward aridity; the orange bars are phases of unsteady climate. **(A)** Termination of the African Humid Period according to terrigenous input from the Senegal River (deMenocal et al. 2000); **(B)** Saharan pollen record from Lake Yoa (Kröpelin et al. 2008); **(C)** tree rings of *Cupressus dupreziana* (Cremaschi et al. 2006); **(D)** cultural evolution of the Garamantian civilization (Mori et al. 2013); **(E)** Lake Wadhwana fluctuations in the Thar Desert (Raj et al. 2015); **(F)** record of Arabian Sea upwelling (Gupta et al. 2003); **(G)** changes in the Indus River discharge (Staubwasser et al. 2003); **(H)** cultural evolution of the Indus civilization (Dixit et al. 2014).

AFFILIATIONS

[1]Dipartimento di Scienze della Terra "A. Desio", Università degli Studi di Milano, Italy

[2]CaSEs - Complexity and Socio-Ecological Dynamics group, Barcelona, Spain

[3]Department of Humanities, Universitat Pompeu Fabra, Barcelona, Spain

[4]School of Geography, Archaeology, and Environmental Studies, University of the Witwatersrand, Johannesburg, RSA

[5]ICREA, Barcelona, Spain

CONTACT

Andrea Zerboni: andrea.zerboni@unimi.it

REFERENCES

Cremaschi M et al. (2006) Holocene 16: 293-303

Cremaschi M, Zerboni A (2009) C R Geosci 341: 689-702

DeMenocal PB et al. (2000) Quat Sci Rev 19: 347-361

Dixit Y et al. (2014) Geology, doi: 10.1130/G35236.1

Enzel Y et al. (1999) Science 284: 125-128

Gasse F (2000) Quat Sci Rev 19: 189-211

Gupta AK et al. (2003) Nature 421: 354-357

Kröpelin S et al. (2008) Science 320: 765-768

Kuper R, Kröpelin S (2006) Science 313: 803-807

Madella M, Fuller DQ (2006) Quat Sci Rev 25: 1283-1301

Manning K, Timpson A (2014) Quat Sci Rev 101: 28-35

Mori L et al. (2013) In: Mori L (Ed) Life and Death of a Rural Village in Garamantian Times. All'Insegna del Giglio, 375-387

Raj R et al. (2015) Palaeogeogr Palaeoclimatol Palaeoecol 421: 60-74

Staubwasser M et al. (2003) Geophys Res Lett 30, doi: 10.1029/2002GL016822

doi: 10.22498/pages.24.2.62

Global megadrought, societal collapse and resilience at 4.2-3.9 ka BP across the Mediterranean and west Asia

Harvey Weiss

Across the Mediterranean and west Asia, the effects of the 4.2-3.9 ka BP megadrought included synchronous collapse of the Akkadian Empire in Mesopotamia, the Old Kingdom in Egypt and Early Bronze Age settlements in Anatolia, the Aegean and the Levant.

Decadal to century-scale megadroughts are a recently discovered but now well-documented feature of the Holocene. A major and much-discussed example is the abrupt global megadrought and cooling at ca. 4.2-3.9 ka BP (2200-1900 BC), called "4.2 ka BP megadrought" hereafter. Data for this megadrought are derived from analyses of lake and marine sediments, glacial and speleothem cores, and tree-rings. In the eastern hemisphere, these high-resolution proxy records extend across the Mediterranean to east Asia and Australia. The megadrought signal also crossed the African continent, from Algeria and Egypt to South Africa and from the Horn of Africa to the central Sahara and the Gulf of Guinea. In the western hemisphere, the proxy records extend from Greenland and Iceland to the Caribbean, across North America to the Canadian Yukon, and down the western coast of South America from Peru to Patagonia and the Antarctic (Weiss 2015; Zanchetta 2016). Lower resolution proxy data, retrieved by earlier researchers, either failed to note this megadrought or dated it so loosely that synchronous events were obscured (Fig. 1). The newer high-resolution data are, however, virtually impossible to miss or disregard, such that the 4.2 ka BP megadrought has become the focus of volumes of symposia and research conferences annually, alongside scores of journal articles.

For reasons yet unknown, the major global monsoon and ocean-atmosphere circulation systems were deflected or weakened synchronously at 4.2 ka BP, causing major, century-scale precipitation disruptions and failures. The most notable of these global deflections, and the most regionally extensive, are also the most highly resolved in paleoclimate proxy records and are themselves linked to highly resolved regional archaeological records - a captivating and fast-growing research situation!

The very highest resolution records for the 4.2 ka BP megadrought include, prominently, the estimated 30-50% reduction in precipitation delivered by the Mediterranean westerlies in the eastern hemisphere, where they provide for dry-farming and irrigation agriculture across the Aegean, Levant, Anatolia, Mesopotamia, and Iran. Among these highest resolution archives are Mediterranean and Red Sea marine sediment cores, Italian, Albanian and Anatolian lake sediment cores (Weiss 2015), and recently announced Greek and Iranian speleothem cores with sub-decadal sampling intervals. Synchronous disruptions for the Indian Summer Monsoon are indicated at very high resolution at the Mawmluh Cave (Berkelhammer et al. 2012), with six-year sampling intervals, at paleolake Kotla Dahar (Dixit et al. 2013), and also now at Lake Rara in the Himalayas (Nakamura et al. 2016), each presenting precipitation proxies for the Indian subcontinent and the monsoon's contribution of 80% of Nile River flow (Welc and Marks 2014). Further east, the trail of high-resolution aridification records extends to Inner Mongolia and to eastern China, where East Asian Summer Monsoon instabilities affected major Late Neolithic settlement systems (Donges et al 2015), and to Australia, where abrupt, dramatic and sustained weakening of the Indonesian-Australian Summer Monsoon is speleothem documented (Denniston et al 2013).

Also impressive are the high-resolution records in the western hemisphere, which include the ice core at Mt. Logan, Yukon (USA), with 10-year sampling intervals. Here, analysis indicates "major enhanced meridional flow coincident with major changes in the Pacific paleorecords of the balance between El Niño and La Niña, suggesting with other records that 4.2 ka BP inaugurated the 'modern' ENSO world" (Fisher 2008). Similarly, the annual resolution of Great Basin tree rings indicates severe cooling with "no evidence that treelines have established at these altitudes since before the 2200 BC treeline drop" and "quite possibl[y] that high

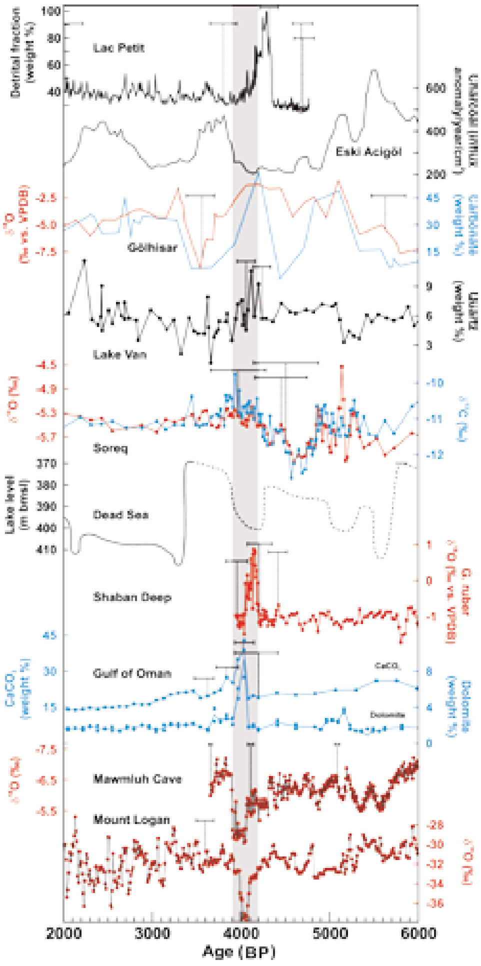

Figure 1: Multi-proxy stack display of older, low resolution and more recent Mediterranean westerlies paleoclimate proxy data for 4.2-3.9 ka BP megadrought (and Alpine flooding), with the high-resolution proxies at Mawmluh Cave, India, and Mt. Logan, Yukon. Bars are proxy uncertainty (at two standard deviations) dating. Grey vertical band indicates ca. 300-year period of collapse, abandonment and habitat tracking in eastern Mediterranean and west Asia synchronous with megadrought (M. Besonen and H. Weiss).

elevation ecosystems are now responding in a manner unprecedented in approximately 4,200 years" (Salzer et al. 2013). In sum, the high-resolution data now available indicate that this was a unique and global Holocene climate event second only to the 8.2 ka BP event in magnitude, but perhaps twice its duration. Hence, the onset of the 4.2 ka BP megadrought has been proposed to mark the middle to late Holocene transition (Walker et al 2012).

Societal collapse, regional abandonments and habitat tracking

How did societies adapt to what was a 200-300 year mid-Holocene megadrought? The proxy records for the interruption of the Mediterranean westerlies and the Indian Summer Monsoon are located where regional archaeological records are most numerous and highly resolved: the Mediterranean, the Levant, Egypt, Turkey, and Mesopotamia. Here, widely distributed and organizationally different, cereal-agriculture-based societies collapsed synchronously and coincident with the megadrought. The archaeological record for these societal collapses includes (1) intensive regional settlement surveys (2) high-resolution radiocarbon dating for abrupt abandonments in dry-farming domains across the scales of settlement, from villages to cities, and (3) epigraphic and radiocarbon data for the collapses of the region-wide, expanding Mesopotamian Akkadian Empire and the Nile-based Egyptian Old Kingdom (Ramsey et al. 2010; Weiss et al. 2012; Davis 2013).

In these regions dependent upon rain-fed agriculture, the adaptive societal response linked with abandonment was habitat-tracking to riparian, paludal and karstic refugia. Region-wide settlement surveys suggest that the populations abandoning the rain-fed plains of southwestern Turkey, western Syria and northern Mesopotamia became the habitat-tracking populations that settled along the banks of the Euphrates River and the karst-spring fed Orontes River (Fig. 2). Similar habitat tracking occurred synchronously in the southern Levant and in the western Mediterranean.

Pastoralist adaptations

The Amorites, a large tribal confederation of pastoral nomad "campers", also exploited the Mesopotamian and Levantine landscapes, traversing the middle Euphrates River valley seasonally to steppe lands and dry-farming plains for sheep-flock forage. The abrupt desiccation disrupted this ancient seasonal pattern, forcing the tribal groups to seek refugia along and down the Euphrates River. This infiltration of southern Mesopotamian urban kingdoms prompted their dynasts to construct the "Repeller of the Amorites" wall recorded in contemporary records. The wall proved porous, however, and within a few generations the former pastoralists' descendants became the Amorite rulers of Babylon. Indeed, the megadrought at 4.2-3.9 ka BP, serendipitously the best-documented period in cuneiform sources for southern Mesopotamia, was previously understood to represent inherently maximizing irrigation-based agriculture and hypertrophic city growth. But its anomalous character, a function of demographic and subsistence forces unleashed by the 4.2 ka BP megadrought, now encourages environmental historicization.

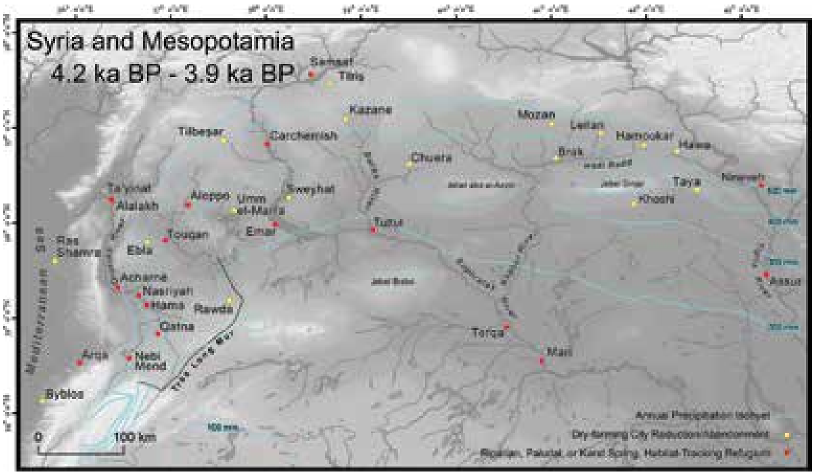

Figure 2: Syria and Mesopotamia, 4.2-3.9 ka BP, indicating major dry-farming settlement abandonments and reductions and habitat tracking to riparian, paludal and karstic refugia (S. Maples and H. Weiss).

What caused the resettlement?

An explanation for the resettlement of Mesopotamian dry-farming domains, and the opportunistic sedentarization of formerly pastoralist Amorites at the abrupt ca. 1900 BC return of pre-aridification precipitation, now comprises a major anthropological and archaeological challenge, even though the historical moment is well-documented. The resettlement swiftly generated the famous warring kingdoms associated with the empire of Shamshi-Adad of Assyria and massive military struggles for rain-fed land and imperial power across west Asia. Resettlement is apparently not self-evident: for instance, the post-megadrought abandonment of the central Maya Lowlands in the 9th century AD continued.

Similarly, the variabilities within several other Holocene societal collapses are now available for cross-cultural exploration, including the 3.2 ka BP megadrought that caused Mediterranean and west Asian collapses and resettlements; the megadrought-induced 11th century AD collapse of the Tiwanaku state and its raised–field agriculture at Lake Titicaca in western Bolivia and subsequent highland-lowland habitat tracking; the synchronous Wari empire collapse in Peru that was followed by the Late Intermediate Period surge of warfare, elevated morbidity and excess mortality; the 13th century AD "Great Drought" and Ancestral Pueblo regional abandonments and habitat tracking to refugia in southwest North America; and the collapse and abandonment of the expansive "hydraulic city" at Angkor, Cambodia, following 13th-14th century AD decadal droughts and high-magnitude monsoons.

Future research

As a new generation of researchers amass high-resolution data for megadrought and societal responses at 4.2 ka BP, developing research arenas include Greece and the southern Levant, where the megadrought data are certain but some regional archaeological surveys remain insufficiently resolved; the Indus Valley, where the paleoclimate data are also clear but archaeological periods require better dating; China, where northern regions were desiccated and abandoned (Yang et al. 2015) while Yellow River extreme flooding is reported during Longshan-period urban collapse; North America, where the megadrought is close in time and space with the earliest crop domestication in the Yucatan and eastern North America, thereby challenging current origins of agriculture hypotheses; and Peru, where the 4.2 ka BP event may have conditioned abandonment of the Late Pre-ceramic Supe Valley cities (Weiss 2015).

Societal resilience

The multi-century 4.2 ka BP megadrought generated adaptive societal collapse, abandonment and habitat tracking across hydrologically varied landscapes. These proved to be resilient strategies for the diverse peoples and polities of the Mediterranean and west Asia. Previously mysterious and unexplained, these synchronous ancient events are now historical processes linking dynamic societies and abrupt Holocene megadrought. Moreover, the evidence prompts further proxy resolution, modeling and explanation.

AFFILIATION
School of Forestry and Environmental Studies, Yale University, New Haven, USA

CONTACT
Harvey Weiss: harvey.weiss@yale.edu

REFERENCES

Berkelhammer M et al. (2012) In: Giosan L et al. (Eds) Climates, Landscapes, and Civilizations. American Geophysical Union, 75-87

Davis J (2013) Am J Arch 117: 527-533

Denniston R et al (2013) Quat Sci Rev 78:155-168

Dixit Y et al. (2014) Geology 42: 339-342

Donges et al (2015) Clim Past 11: 709-741

Fisher D et al. (2008) Holocene 18: 667-677

Nakamura A et al. (2016) Quat Int 397: 349-359

Ramsey CB et al. (2010) Science 328: 1554-1557

Salzer MW et al. (2013) Clim Dyn 42: 1517-1526

Walker M et al. (2012) J Quat Sci 27: 649-659

Welc F, Marks L (2014) Quat Int 324: 124-131

Weiss H et al. (2012) In: Weiss H (Ed) Seven Generations since the Fall of Akkad. Harrassowitz, 163-192

Weiss H (2015) In: Meller H et al. (Eds) 2200 BC – a climatic cause for the collapse of the Old World, 35-52

Yang X (2015) PNAS 112: 702-706

Zanchetta G et al. (2016) Alp Med Quat 29: 5-17

doi: 10.22498/pages.24.2.64

Revisiting human-environment interactions in Chaco Canyon and the American Southwest

Julio L. Betancourt[1] and Christopher H. Guiterman[2]

Chaco Canyon was the center of a regionally integrated system. Despite a century of research, questions remain about its rise and fall, and the role of human-environment interactions. The answers may lie in current events and new tools and perspectives.

Chaco Canyon in northwestern New Mexico, USA, boasts a spectacular array of prehistoric ruins, meriting status as a US National Historical Park and UNESCO World Heritage Site. First excavated 120 years ago, Chaco Canyon may be the most-studied archaeological site in the USA, motivating hundreds of publications and even its own queryable archive and database (www.chacoarchive.org/cra/). The desolate canyon, a marginal and unpredictable environment, supported the Ancient Puebloans in developing a complex society and regionally integrated system that, at its nadir in the 11th century, was centered on Chaco and spanned >50,000 km^2 (Fig. 1). In popular literature, Chaco's genesis inspires awe - "a dazzling show of wealth and power in a treeless desert" (Fernández-Armesto 2001) - while its collapse stirs deep reflection about "environmental impact and climate change intersecting" (Diamond 2005).

Despite more than a century of focused research, there are still many unanswered questions (e.g. Plog and Heitman 2010). The Chaco Phenomenon emerged quickly ~AD 850 from dispersed rural communities subsisting on maize, beans and squash, flourished for a few centuries, then collapsed between AD 1130 and 1150. In its heyday, the Chaco Phenomenon was distinguished by planned architecture of multistoried great houses; shared ceramic traditions and rituals; intensive agriculture and sophisticated water-control features; long-distance trade of luxury items (cacao, macaw and parrot feathers, copper bells, turquoise, and seashells); and an extensive network of well-constructed roads.

Integrating a regional human-environmental system

Today, Chaco is deficient in natural resources (Fig. 1), giving rise to the idea that Chaco Society was a regionally integrated system that relied on resource-rich areas and outlying communities. Chaco could have acted as a center for storage and redistribution of surplus food, particularly maize, by a small and elite population housed in the canyon, or as a religious center into which food and other goods flowed during pilgrimages that reinforced system-wide religious authority. Others counter that Chaco looked very different 1,000 years ago, and was a productive agricultural center able to sustain a large population throughout most of its three-century tenure. These differing perspectives on the Canyon's environment and its social structure lead to widely ranging population estimates during the Chaco Phenomenon, from <10,000 to >100,000 people (Minnis 2015).

Timber and fuel for great houses

The Ancient Puebloans at Chaco quarried sandstone blocks and logged hundreds of thousands of trees, mostly big conifers that do not grow locally today, to build the dozen or more great houses, considered the largest buildings in North America north of Mexico until the 19th century. Plant macrofossils from packrat middens on the canyon slopes showed that ponderosa pine (*Pinus ponderosa*), the main architectural timber, grew locally only as scattered individuals during the late Holocene - not enough to sustain architectural needs (Betancourt and Van Devender 1981). Engelmann spruce (*Picea engelmannii*) and subalpine fir (probably *Abies lasiocarpa*), which made up a quarter of the architectural wood (Betancourt et al. 1986), last grew in the canyon 12,000 years ago, and must have been logged from mountaintops >75 km away. Tree-growth patterns show that, prior to AD 1020, nearly all of the timber was procured from the Zuni Mountains >80 km to the southwest (Guiterman et al. 2016). Later during the mid-11th century Chacoan fluorescence, both tree-growth patterns and strontium isotopes indicate that most of the timber came from the Chuska Mountains >75 km to the west (English et al. 2001; Reynolds et al. 2005; Guiterman et al. 2016). This shift in tree sources is associated with nearly two decades of drought conditions in the Zunis that were apparently less marked in the Chuskas (Fig. 2). Along with timber, the Chuskas were a major source for stone tools, pottery and maize. The area also emerges as a primary resource for deer, rabbits and prairie dogs consumed at Chaco (Grimstead et al. 2016).

While timber and other resources were clearly procured from long distances, fuelwood was available locally. The packrat midden record shows persistent and ubiquitous pinyon pine throughout the late Holocene until it was locally extirpated between AD 700 and 1500. To this day, pinyon populations show no sign of recovery. So the question is not just what caused pinyon's extirpation, but also what has prevented its recovery? The explanation could well involve climate or woodcutting. Under a woodcutting scenario (Samuels and Betancourt 1982), Chacoans could have easily wiped out the woodland in a couple centuries, likely pushing firewood gathering to more distant

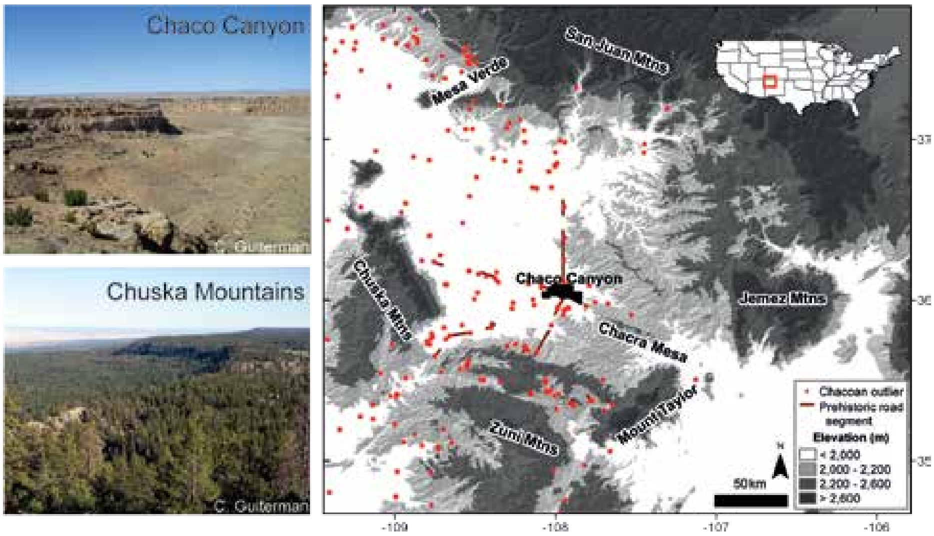

Figure 1: The regional system centered on Chaco Canyon, but associated "outlier" communities populated the western half of the San Juan Basin. Distant areas like the Chuska Mountains were far richer in timber and other resources than Chaco Canyon at the time, as they are now.

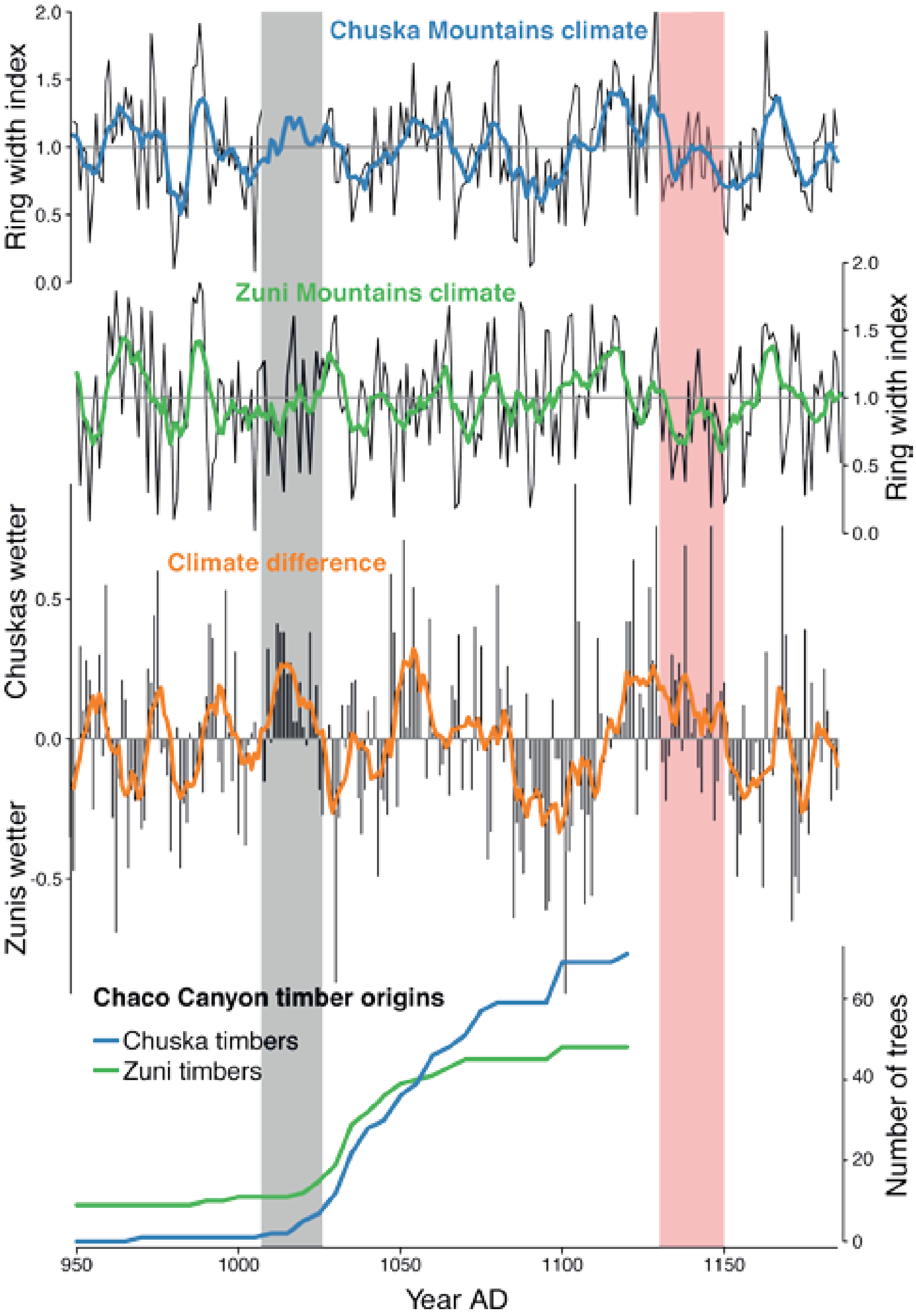

Figure 2: Local climates and timber extraction. Precipitation-sensitive tree-ring-width chronologies from the Chuska and Zuni Mountains show sub-regional differences in the timing, duration and severity of drought. One period (AD 1007-1026; grey shading) coincides with the arrival of Chuska timbers to Chaco Canyon. The 12th century megadrought (AD 1130-1150; red shading) probably initiated collapse at Chaco and was longer and deeper in the Chuskas than the Zunis. Bold lines in the top three panels are seven-year running averages. The third panel shows the difference between the Chuska and Zuni tree-ring chronologies. Data from Guiterman et al. (2016).

stands, including nearby Chacra Mesa. Ultimately, this could have reduced nearby seed sources from which local pinyon populations could regenerate.

A possible role for megadrought

Impacts of the recent 2000s drought in the region underscore a climate explanation. Over the last two decades, severe droughts in western USA have resulted in widespread and synchronized ecological disturbances, including wildfires, pine beetle outbreaks, and tree die-offs (Williams et al. 2013). These events have inspired a flurry of research on the impacts of hotter drought associated with anthropogenic warming, but both archaeologists and paleoecologists, including the authors, are currently revisiting the enigmatic ecological footprints of past droughts. Could pinyon at its lower and dry limits in Chaco Canyon have been wiped out by the mid-12th century megadrought? Occurring during the height of the unusually dry Medieval Climate Anomaly (MCA; AD 900-1300), the mid-12th century megadrought far exceeded the severity, duration and extent of subsequent droughts (Woodhouse et al. 2010). Although ecological impacts are less well-documented, we do know that this, and other MCA droughts, synchronized extensive wildfires from California (Swetnam et al. 2009) to Colorado (Calder et al. 2015). It is likely that these droughts also produced widespread tree die-offs. As part of an ongoing study to assess past ecological disturbances in the Chuska Mountains, one of us (CHG; unpublished data) sampled over 1000 trees and found only eight that were established before AD 1150, with just three trees surviving the mid-12th century megadrought, which was apparently more severe in the Chuskas than in the Zuni Mountains to the south (Fig. 2).

Future questions

Did impacts of the extended mid-12th century drought in the Chuskas have a cascading effect on the Chaco Core and its regional system? Was the shift in sources of architectural timber from the Zuni to the Chuska Mountains around AD 1020 driven by asynchroneity in hydroclimate variability across the region, perhaps related to shifting epicenters of droughts and pluvials? Did sub-regional syn- and asynchroneities in climate and ecosystems, perhaps changing over time, determine Ancestral Puebloan movements initially to Chaco and later to other sites during abandonment? This is precisely the modeling approach taken by Bocinsky and Kohler (2014) in using tree-ring data to model the rain-fed, maize agricultural niche across the US Southwest. The same could be done for other essential resources, which could have shifted dramatically with large and synchronized disturbances driven by drought. Although Chaco Canyon has been well studied, most of the excavations and the published literature happened in the 20th century. The prospects for new research at the intersection of human impacts and climate change are not only exciting but in order.

AFFILIATIONS

[1]US Geological Survey, Reston, USA
[2]Laboratory of Tree-Ring Research, University of Arizona, Tucson, USA

CONTACT

Julio L. Betancourt: jlbetanc@usgs.gov

REFERENCES

Betancourt J et al. (1986) American Antiquity 51: 370-375

Betancourt J, Van Devender T (1981) Science 214: 656-658

Bocinsky R, Kohler T (2014) Nature Comm 5, doi:10.1038/ncomms6618

Calder W et al. (2015) PNAS 112: 13261-13266

Diamond J (2005) Collapse: How Societies Choose to Fail or Succeed, Penguin Books, 571 pp

English N et al. (2001) PNAS 98: 11891-11896

Fernández-Armesto F (2001) Civilizations: culture, ambition, and the transformation of nature, The Free Press, 560 pp

Grimstead D et al. (2016) Geoarchaeology, doi: 10.1002/gea.21545

Guiterman C et al. (2016) PNAS 113: 1186-1190

Minnis P (2015) In: Heitman C, Plog S (Eds) Chaco Revisited: New Research on the Prehistory of Chaco Canyon, New Mexico. University of Arizona Press, 305-321

Plog S, Heitman C (2010) PNAS 107: 19619-19626

Samuels M, Betancourt J (1982) Environ Manage 6: 505-515

Swetnam T et al. (2009) Fire Ecol 5: 120-150

Williams P et al. (2013) Nature Clim Change 3: 292-297

Woodhouse C et al. (2010) PNAS 107: 21283-21288

doi: 10.22498/pages.24.2.66

Climatic changes and collapses in Maya history

Tim Beach[1], S. Luzzadder-Beach[1], N. Dunning[2] and D. Cook[3]

Archaeology and paleoclimatology provide insights into the vagaries of Maya history and climate. Although millions of Maya persist today, three main historical declines coincide with drought records. These are important examples of humanity's complex interactions with drought and environmental change.

The idea that the Classic Maya of Central America "collapsed" dates back to at least the 19th century (Luzzadder-Beach et al. 2012). Explorers like Stephens and Catherwood, in the 1840s, documented many ancient Maya cities in stages of decay. These writings and pictures of temple ruins enshrouded by tropical forest provided imagery of a lost Maya world. Both "collapses" (profound reductions in population or reductions in social complexity) and "declines" (depopulations) occurred over Maya history. Archaeologists have long studied both, and the roles that climate may have played has attracted worldwide attention, but how this great culture persisted is even more interesting (Beach et al. 2015). Although there is convincing paleoclimatic evidence for droughts during several Maya periods, the archaeological evidence for collapse during any of these periods remains coincidental.

The vagaries of Maya cities varied across time and space. In the northern Yucatán, the city of Mayapán collapsed around 1440 AD and Chichén Itzá declined around 1250 AD. The Maya heartland cities from Uxmal southward to Copán flourished into the 9th and 10th centuries AD (Fig. 1). El Mirador and other early urban centers collapsed much earlier, around 150 AD. These lines of evidence suggest three main cessation periods: The Late Preclassic (300 BC-250 AD) or just after, the Late and Terminal Classic (700-1000 AD), and the Early Post Classic (1000-1100 AD). Several paleoclimate records indicate drier conditions either during or near these three periods of social and cultural upheaval (Fig. 2), and some studies linked the Middle Classic hiatus, a period of stagnation (ca. 550 AD) around Tikal, to drought (Beach et al. 2015).

But scholars debate *when* collapse actually occurred or *if* any specific collapse occurred because millions of Mayan language speakers still exist. One view is that the collapse occurred mainly after European conquest and subsequent indigenous population declines, caused by European diseases, forced religious and social conversions, and cultural truncation. One vivid example of this was Europeans burning Maya books, terminating a millennia-old glyph-based language.

A key region of Maya lowlands collapse was the Elevated Interior Region (EIR), which lies prone to water stress far above perennial water sources. Here the Maya built various forms of water storage such as the many reservoirs at the great cities of Tikal and Caracol (Beach et al. 2015). The Maya tended to overbuild reservoirs to withstand rainfall variability, but these systems may not have been survivable under severe droughts. Indeed, the EIR was an appealing place in the wetter Preclassic and drought remained manageable even in the drier Late Preclassic, but later droughts may have proved insurmountable (Fig. 2).

The Maya Collapse literature includes a legion of causes, such as droughts, soil deterioration, hurricanes, epidemics, and seismicity, as well as social upheavals in religion, warfare, and trade routes (Beach et al. 2015). Climate change could have led to crop failures, famine and refugees. These in turn could have led to other environmental or social changes, like the Maya rejection of rulers, warfare or changes in trade routes away from the EIR, which could never regenerate in this drought-prone land (Turner and Sabloff 2012).

Like other tropical climates, the Maya lowlands has pronounced wet and dry seasons. The May through November wet season arises from atmospheric instability of the intertropical convergence zone (ITCZ) and the December to May dry season is caused by air stability from the subtropical high pressure (STHP). Rainfall comes from convection and convergence systems of all scales and varies both inter-annually and geographically, ranging from 500 mm per annum in northwest Yucatán to above 3000 mm in the southern mountains (Fig. 1).

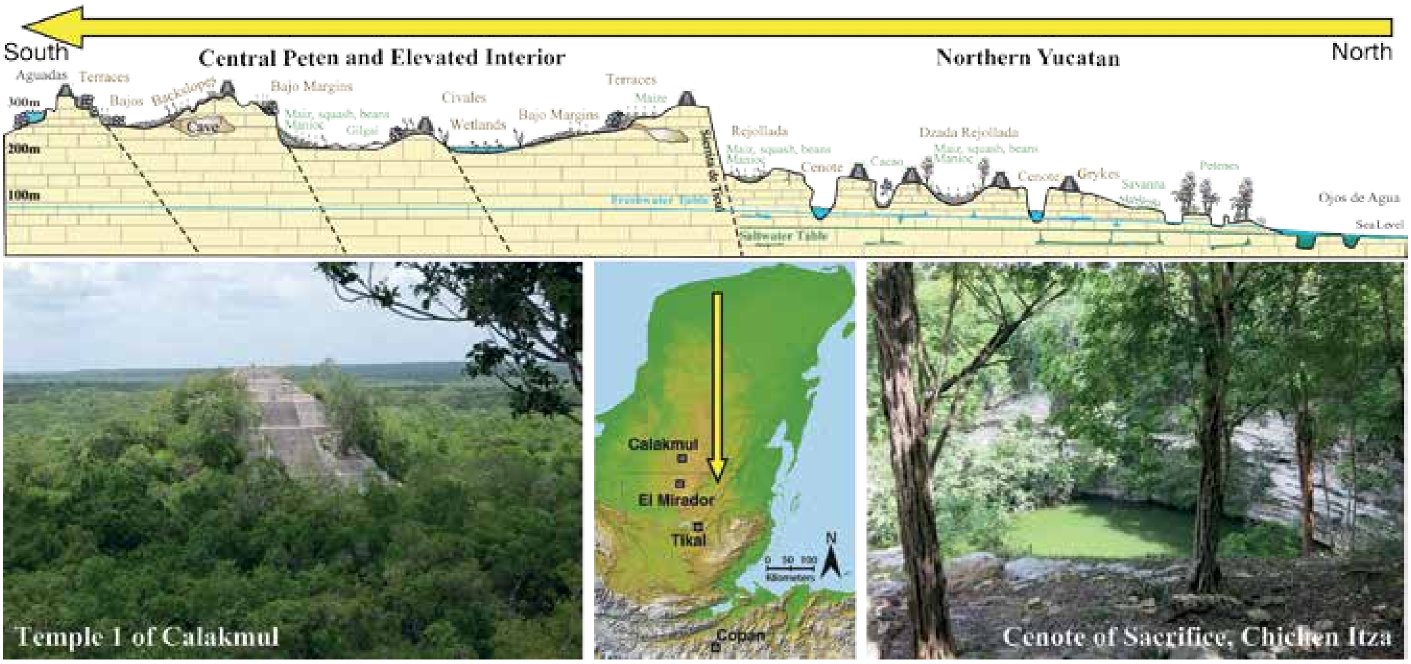

Figure 1: Map and landscape diagram of the Yucatán Peninsula in Central America showing the relationship between the Maya lowlands and the more elevated interior.

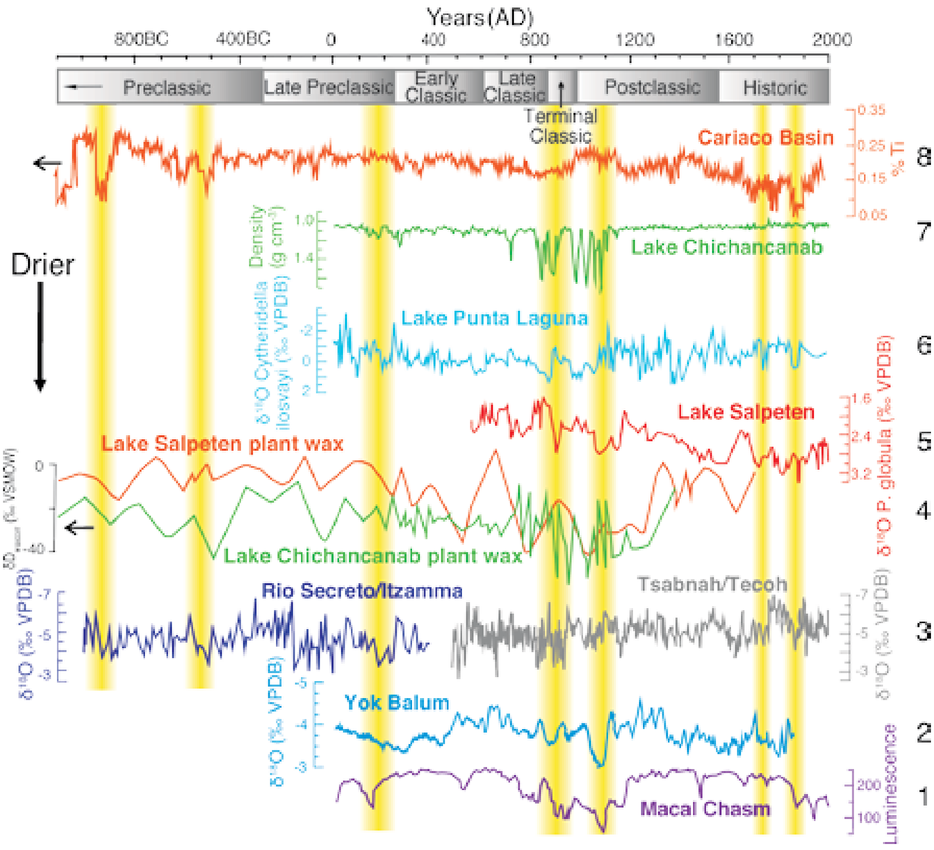

Figure 2: Climate proxy records overview for the Maya lowlands with droughts highlighted in yellow (redrafted after Luzzadder-Beach et al. 2016). See text for references to numbers in the right-hand column.

The Maya lowland's climate change record derives from cave speleothems, and lake and marine sediments (Fig. 2). Speleothem records are especially important because of their finer chronology that can overlap with instrumental records. Speleothems that can accurately fit instrumental records provide confidence for hindcasting past climate and overlapping the many but coarser-resolved lake records.

These records indicate three key arid periods that coincide with declines of Maya polities. The earliest such drought occurs in the last century of the Late Preclassic (150-250 AD), and three northern Yucatán and southern Belize speleothem records indicate drought at or just after this time (Fig. 2.1, 2.2, 2.3). Sediments from the northern Yucatán lakes and the Cariaco Basin provide overlapping evidence (Figure 2.4, 2.6, 2.7, 2.8). The archaeological evidence includes the collapse of the giant site of El Mirador and allied centers, as well as the iconic Preclassic site of San Bartolo and coastal site of Cerros (Fig. 1), but elsewhere there were mainly temporary declines and social upheavals (Dunning et al. 2012; Iannone 2014). A speleothem record from the heart of the collapse zone in Guatemala's Petén may help us frame this drought.

The Middle Classic hiatus (ca. 550 AD) provides a less-convincing case. Studies from around the world indicate a global cooling event (Büntgen et al. 2016) and at least two large volcanic eruptions (one possibly from Mesoamerica) from 536-540 AD (Sigl et al. 2015). Some studies link drought and cultural declines at this time, but most link the hiatus with war mainly around the Tikal region (Iannone 2014).

The Terminal Classic saw the decline of many more cities, ranging spatially from Yucatán to Honduras and temporally from about 700 to 900 AD (Webster 2002). A few cities, especially coastal plain or riverine ones like Lamanai, flourished longer (Beach et al. 2015). The climatic evidence also has a wide geographic range from northern Yucatán to the Cariaco Basin, though some records are more equivocal (Fig. 2). One key climate archive has been Laguna Chichancanab (Fig. 2.4, 2.7; Hodell et al. 1995), where the scientific study of the Terminal Classic drought began (Beach 2016). Several climate records also indicate droughts in the Early Post Classic (Fig. 2.1, 2.2, 2.5, 2.7).

Some research also suggests the Late-Terminal Classic drought period had more extreme events like hurricanes, which could have exacerbated drought impacts and masked their severity (Frappier 2013). Indeed, the Maya dealt with overlapping hazards in the Late- and Terminal Classic. Hurricane runoff can damage soils and trees and lead to an increased risk of forest fire from fuel build-up. Sea-level rise affected many coasts, and the lack of large coastal Maya cities suggests coastal hazards played some role in ancient Maya urban geography (Dunning et al. 2012).

The Terminal and Postclassic droughts would have been challenging to any civilization, and especially so in the Maya heartland with its dearth of permanent water sources. Some studies suggest that the Maya here started building reservoirs in the Late Preclassic and Early Classic coincident with or after drought, which may have offered stability for centuries. But sedimentation reduced storage capacity so that by the intense droughts of the Late to Post Classic water storage (resiliency) had diminished (Beach et al. 2015). Also, the large-scale abandonment of the Terminal Classic may have reset Maya trade and production geography, which the Early Postclassic drought reinforced. More droughts occurred later in the Little Ice Age and the long trend of Late Holocene drying (Wanner et al. 2008) may have made the EIR unattractive. Thus, the EIR, erstwhile center of Maya Civilization, lost its appeal by the Postclassic. Thereafter, the Maya chose to live, trade and farm near perennial water sources along the Maya lowlands' margins until European conquest.

The 21st century is bringing new climate challenges to the Maya lowlands. The IPCC anticipates that temperatures will rise and precipitation fall, increasing water stress (Margrin et al. 2014). We still need more research that can pair climate histories with archaeology to better understand the role of climate in Maya history. New paleoclimate research from this data-poor region can complement and extend modern records of climate and improve models of future climate change. Likewise, archaeological research that can identify and date features that signify adaptation to droughts, like dams, canals and water harvesting, may help us identify critical thresholds in social responses to water stress.

AFFILIATIONS

[1]Geography and the Environment, The University of Texas at Austin, USA
[2]Geography, The University of Cincinnati, USA
[3]School of Arts, Australian Catholic University, Brisbane, Australia

CONTACT

Tim Beach: beacht@austin.utexas.edu

REFERENCES

Beach T et al. (2015) Quat Sci Rev 124: 1-30

Beach T (2016) Global Planet Change 138: 1-2

Büntgen U et al. (2016) Nat Geosci 9: 231-236

Dunning N et al. (2012) PNAS 109: 3652-3657

Frappier AB (2013) Geochem Geophys Geosyst 14: 3632-3647

Hodell DA et al. (1995) Nature 375: 391-394

Iannone G (2014) The Great Maya Droughts in Cultural Context: Case Studies in Resilience and Vulnerability. University Press of Colorado, 448 pp

Luzzadder-Beach S et al. (2012) PNAS 109: 3646-3651

Luzzadder-Beach S et al. (2016) Antiquity 90: 426-442

Magrin GO et al. (2014) In: Barros VR et al. (Eds) Climate Change 2014. Part B: Regional Aspects. Cambridge University Press, 1499-1566

Sigl M et al. (2015) Nature 523: 543-549

Turner BL, Sabloff JA (2012) PNAS 109: 13908-13914

Wanner H et al. (2009) Quat Sci Rev 27: 1791-1828

Webster DL (2002) The Fall of the Ancient Maya: Solving the Mystery of the Maya Collapse. Thames & Hudson, 368 pp

doi: 10.22498/pages.24.2.68

Climate change and human impact in Macaronesia

José María Fernández-Palacios[1], S. Nogué[2,3], C. Criado[4], S. Connor[5], C. Góis-Marques[6,7], M. Sequeira[6] and L. de Nascimento[1]

Past climate dynamics have helped shape the endemic ecosystems of Macaronesia. However, these insular ecosystems have since been modified following the arrival of human settlers, who had to adapt to the new environments and resources.

Macaronesia is a biogeographical region with four volcanic archipelagos (Azores, Madeira, Canaries and Cape Verde) in the NE Atlantic Ocean (Fig. 1). These island chains share several endemic genera and the three northernmost ones retain laurel forests, which are widely considered to be impoverished remnants of the Paleotropical Geoflora, distributed around the Tethys Sea during the Cenozoic, and disappeared at the onset of the Pleistocene glaciations.

Owing to their relatively late colonization by humans, oceanic islands offer the best conditions to disentangle the ecological impacts of human activities from those produced by climate shifts or volcanic events. Furthermore, Macaronesia comprises islands that were colonized either by North Africans (Canaries, ca. 2.9 ka BP; Atoche and Ramírez 2011) or later during the European expansion (Azores, Madeira and Cape Verde, 15th century; Fig. 1), allowing diverse cultural impacts to be differentiated. After their arrival, humans had to face and adapt to new environments and climatic conditions, which offered them new resources and provided new challenges.

Past climate change

The Canaries were subject to important climate change in the mid Holocene, namely the end of the African Humid Period, ca. 5.5 ka BP, which induced important shifts in the laurel forest composition, as the more hygrophilous taxa were displaced by more xerophilous ones (Nogué et al. 2013).

Paleoecological studies on Madeira Island are still rare, with the best contribution relating to the Piedade aeolian deposits (Goodfriend et al. 1996). An analysis of these deposits spanning the last 300 ka revealed changing plant cover through time, due to climate and sea-level shifts, as well as an abrupt change in vegetation following the arrival of the Portuguese.

On the Azores, paleoclimatic variations have been detected in sediments on Pico Island. Diatoms and geochemical indicators revealed several arid phases during the last 5000 years and an overall aridity trend linked to Atlantic sea-surface temperatures (Björck et al. 2006). However, vegetation on the Azores changed little in response to these climatic shifts (Connor et al. 2012).

Unfortunately, there are few paleoecological and paleoclimate studies in Cape Verde. Records from marine terraces, however, also point towards oceanic temperatures in this basin being warmer than the present ones during the Last Interglacial.

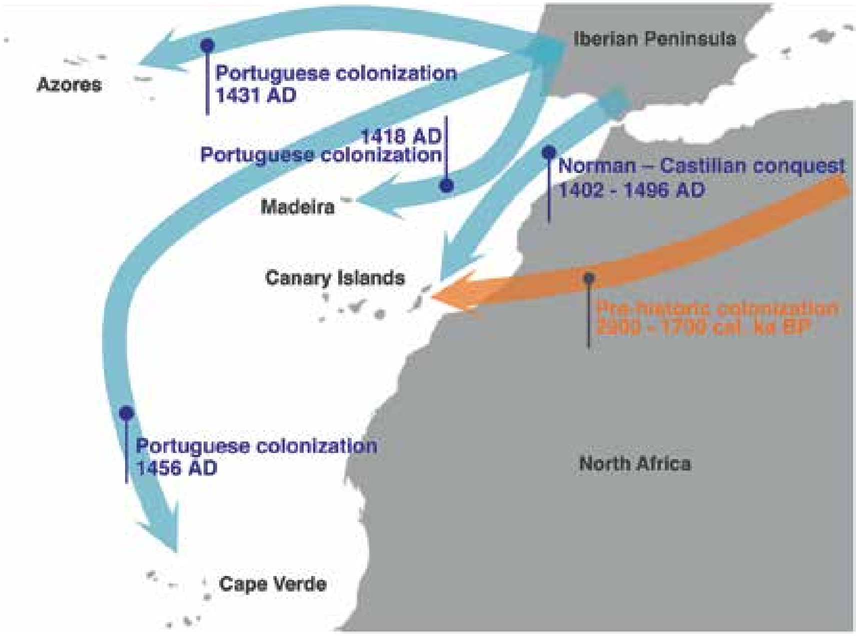

Figure 1: Human colonization of the islands of Macaronesia at prehistoric (orange arrow) and historical times (blue arrows).

Human colonization, impact and adaptation

The trade winds are lifted by the Canarian mountains, creating a year-round humid zone which provides the laurel forest with a refugium to withstand the summer aridity of the Mediterranean climate. This humid zone, without analogue in North Africa during the Holocene, was an unknown environment for the arriving aborigines, where they found species offering new types of timber and fruits. Conversely, bronze or iron, known by early settlers, were not available in Macaronesia due to the volcanic origin of the islands; this led to a cultural decline to a level of the Stone Age (Atoche 2009).

During the pre-historic colonization, the aborigines introduced domestic species and used fire to clear forests and increase ecosystem productivity, hugely impacting the island biota that had evolved for more than 20 Ma in the absence of humans. Ecological impacts included extinctions of plant (de Nascimento et al. 2009) and vertebrate (Rando 2003) species, and ecosystem transformations (de Nascimento et al. 2016).

Recent paleoecological work has revealed significant clearance of vegetation around 2.3 ka BP that did not coincide with any known climatic shift or volcanic eruptions (de Nascimento et al. 2016), indicating that an aboriginal colonization of Gran Canaria must have taken place several centuries earlier than traditionally considered. We also know that there were forests in the highest parts of Fuerteventura, one of the driest islands in the Canaries, based on charcoal remains from trees used as firewood (Machado 2007) and fossil pollen records (de Nascimento, unpublished data). These forests formed under a more humid climate and have been able to subsist during the Late Holocene dry conditions (Yanes et al. 2011). After being cleared by aborigines, the much drier climate impeded the reestablishment of those forests, resulting in the extirpation of several species of trees (Machado 2007) and the loss of a strategic wood resource for future generations.

Changes following European settlement

Since prehistoric times, humans have maximized the use of available resources at different elevations through the exploitation of coasts (saltworks, shellfishing), midlands (agriculture and forestry) and summits (green pastures, sulfur, ice collection; Aguilera et al. 1994), driving the altitudinal configuration

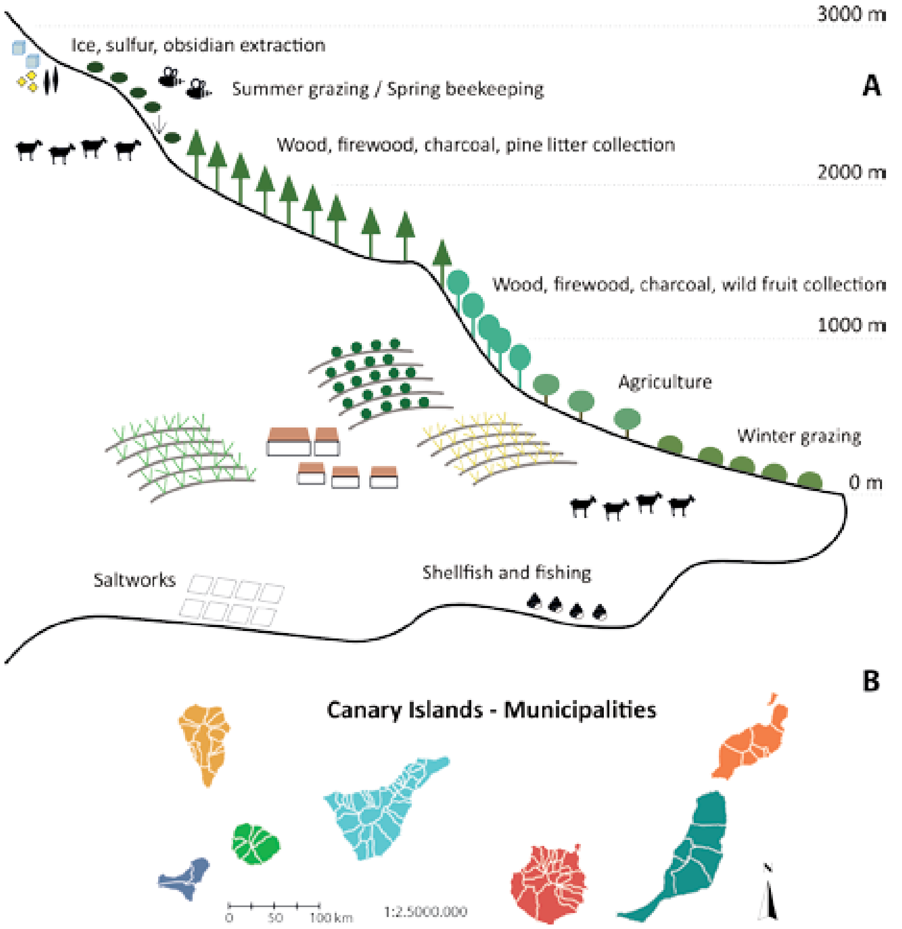

Figure 2: (A) Vertical exploitation of resources following the elevation gradient in Tenerife (Canary Islands; adapted from Aguilera et al. 1994), and **(B)** limits of the municipalities distributed from coast to summit in the Canary Islands.

of the present municipalities in Macaronesia (Fig. 2).

After the Castilian conquest of the Canaries (1402-1496 AD), the new society changed from a pastoral to an agricultural economic base, shifting the cultural impacts abruptly from species threats to deforestation, to provide firewood for sugar mills and land for sugarcane plantations, as well as timber for house and boat building. The archipelago also suffered severe droughts during the 17th and 18th centuries, leading to starvation and massive migrations among islands (García et al. 2003).

Madeira or "Island of Wood" owes its name to the primeval forests that used to cover it, which provided an important source of woods for Portugal. Since Madeira's discovery in 1418, documents show that the exploitation of the forests allowed the building of larger ships for the Portuguese navy (contributing to the expansion of the conquests) and even for the growth in height of Lisbon's buildings. The deforestation in Madeira was so fast that royal decrees from 1493 exist to limit it (Menezes de Sequeira et al. 2007).

The over-exploitation of forests, agriculture, fire and the introduction of alien species led to the extinction or extirpation of native species, such as rails (*Rallus*), the Porto Santo flora, and most probably unknown trees described in historical chronicles (Menezes de Sequeira et al. 2007).

On the Azores, the northernmost archipelago of Macaronesia, islands discovered by colonists that were suitable for growing European crops have since lost much of their original vegetation (e.g. Graciosa island), while the wettest, steepest parts of some islands have retained relatively intact vegetation (e.g. Flores island). Indeed, pollen records show that laurel and juniper forests were distributed at various elevations prior to human colonization (Connor et al. 2012). Historical reports attest to the density and diversity of this original vegetation, along with the presence of species that are now extinct on certain islands (e.g. *Juniperus brevifolia* and *Taxus baccata*). Human impacts were felt even before colonization began, with the release of livestock providing meat for future colonists (Schaefer 2003).

Although the Azorean vegetation was well adapted to recover from disturbances such as landslides and volcanic eruptions, human colonization caused irreversible changes, including the loss of forest trees, local extinctions and the creation of novel vegetation communities (Connor et al. 2012; Schaefer 2003). Timber felling, burning and various agro-pastoral monocultures have shaped the Azorean landscape since the time of colonization. Like many colonized islands, exotic plants today greatly outnumber native species on the Azores, and invasive species are a major threat to the island's native biodiversity (Schaefer 2003).

Finally, Cape Verde is the southernmost and only tropical archipelago of Macaronesia. It is thought to have been uninhabited when the Portuguese colonized it around 1462 AD (Heckman 1985). The first settlers and expeditions described the landscape as having reduced forest cover with a mix of tropical and temperate species. In addition, historians pinpointed that the earlier settlers likely mismanaged the natural resources of the islands and that no attempt was made to create self-sufficient colonies (Heckman 1985).

The primary function of the islands of Cape Verde for the first hundred years was to serve as a base for the slave trade. In addition, many ships stopped to resupply food and water. During the 15th and 16th centuries, large plantations raised cotton, coffee, maize, and sugar cane. During the 17th century, some islands successfully established livestock.

Despite paleoecological and paleoclimate research still in their initial phase in Macaronesia, it has already provided evidence for climate change and human interactions. We are sure that, in the near future, ongoing research of the human impacts on these archipelagos will significantly increase our understanding of colonization processes and cultural evolution.

ACKNOWLEDGEMENTS

We thank Claudia Ruiz for preparing Figure 2.

AFFILIATIONS

[1]Island Ecology and Biogeography Group, Universidad de La Laguna, San Cristóbal de La Laguna, Spain
[2]Geography and Environment, University of Southampton, UK
[3]Department of Zoology, University of Oxford, UK
[4]Department of Geography and History, Universidad de La Laguna, San Cristóbal de La Laguna, Spain
[5]School of Geography, The University of Melbourne, Australia
[6]Madeira Botanical Group, University of Madeira, Funchal, Portugal
[7]Department of Geology, University of Lisbon, Portugal

CONTACT

José María Fernández-Palacios: jmferpal@ull.es

REFERENCES

Aguilera F et al. (1994) Canarias. Economía, Ecología y Medio Ambiente. Francisco Lemus Editor, 361 pp

Atoche P (2009) Zephyrus 63: 105-134

Atoche P, Ramírez MA (2011) An Estudios Atlánticos 57: 139-169

Björck S et al. (2006) Quat Sci Rev 25: 9-32

Connor SE et al. (2012) J Biogeogr 39: 1007-1023

de Nascimento L et al. (2009) J Biogeogr 36: 499-514

de Nascimento L et al. (2016) Holocene 26: 113-125

García R et al. (2003) B Am Meteorol Soc 81: 1037-1039

Goodfriend GA et al. (1996) Palaeogeogr Palaeocl Palaeoecol 120: 195-234

Heckman J (1985) Environ Manage 9: 141-150

Machado MC (2007) Tabona 15: 71-90

Menezes de Sequeira et al. (2007) In: Silva J (Ed.) Árvores e Florestas de Portugal. Vol. 6 Açores e Madeira - A Floresta das Ilhas. Público, 165-196

Nogué S et al. (2013) J Ecol 101: 368-377

Rando JC (2003) El Indiferente 14: 4-15

Schaefer H (2003) Diss Bot 374: 1-130

Yanes Y et al. (2011) Quat Res 75: 658-669

doi: 10.22498/pages.24.2.70

Climate changes and cultural shifts on Easter Island during the last three millennia

Valentí Rull[1], N. Cañellas-Boltà[2], O. Margalef[3], S. Pla-Rabes[3], A. Sáez[4] and S. Giralt[1]

Easter Island's cultural shifts have been explained mostly by anthropogenic forcing and climate changes have been dismissed as relevant drivers of societal change. Recent findings demand a more complex scenario in which climatic, ecological and cultural factors interact.

Easter Island (Rapa Nui) is a small (164 km^2) and remote Pacific island formed by the coalescence of three volcanic cones. The interior uplands are dominated by the Terevaka volcano (511 m elevation) to the north, and the rest of the island is characterized mostly by lowlands. Easter Island has been the home of several scientific enigmas including the chronology of its settlement by people, the origin of the first settlers, and the timing and causes of the disappearance of the ancient Rapanui civilization that built the megalithic statues known as *moai*.

The currently available evidence favors colonization from Eastern Polynesia (Fig. 1) between AD 800 and 1200 (Flenley and Bahn 2003; Hunt 2007; Wilmshurst et al. 2011). However, the breakdown of the ancient Rapanui culture is still debated. The more widely known theory is the occurrence of a cultural collapse following the anthropogenic deforestation of the island and the associated ecological catastrophe or ecocide (Diamond 2005). An opposing view is that deforestation was largely caused by massive tree-seed consumption by introduced Polynesian rats (Hunt 2007). According to this view, cultural collapse was not a consequence of deforestation but of slave trading and the introduction of unknown diseases after the European contact (AD 1722). Hypotheses on the potential influence of climatic changes have been traditionally underrated in favor of anthropogenic explanations (Flenley and Bahn 2003). In the last decade, however, important evidence for climatic shifts on the island and its regional context has grown, and proposals based solely on human pressure have been challenged.

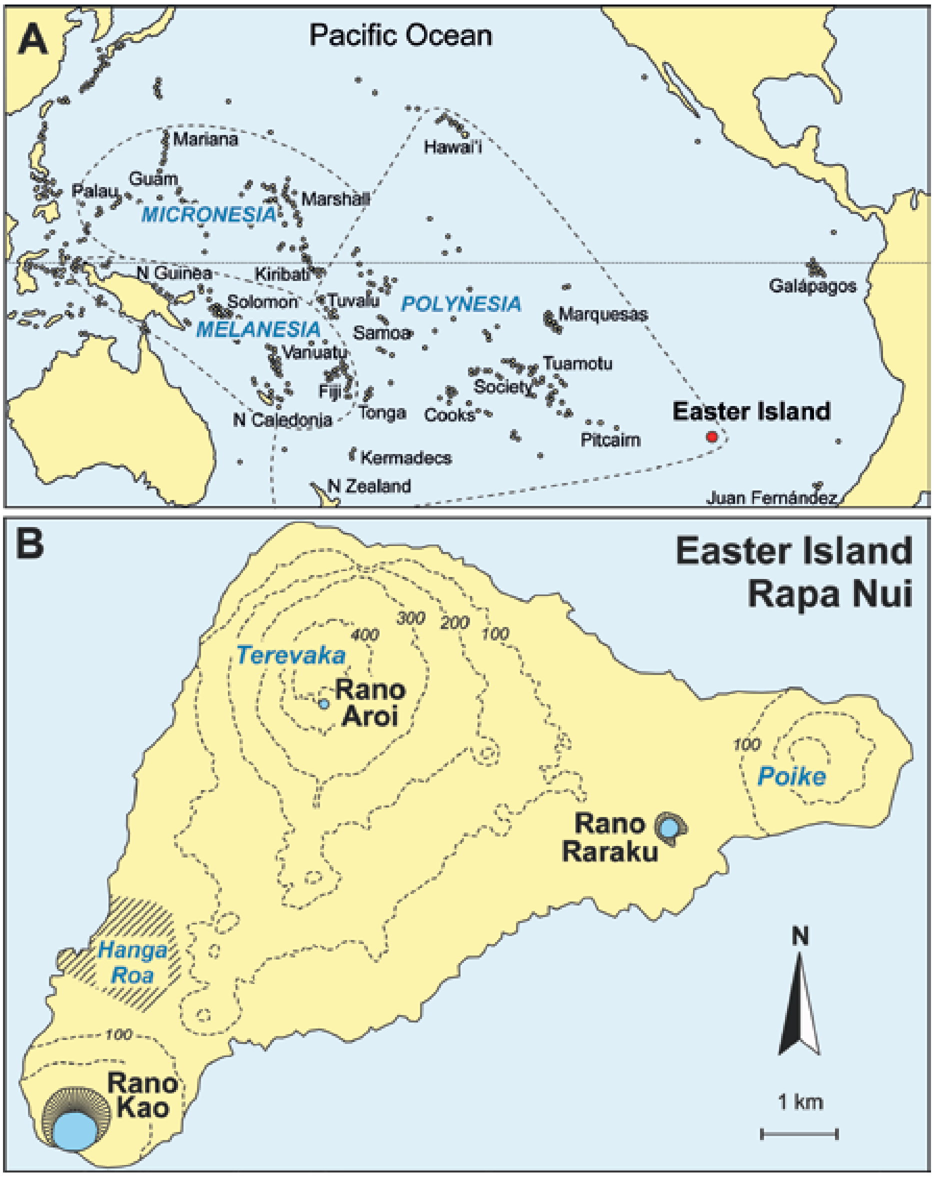

Figure 1: Location map. **(A)** The Pacific Ocean and its main archipelagos (Easter Island is highlighted by a red dot). **(B)** Sketch-map of Easter Island indicating the sites referred to in the text.

Early proposals

The first proposals of a potential influence of climate on ecological and cultural shifts on Easter Island were based on theoretical assumptions, rather than on factual evidence. For example, McCall (1993), by analogy with other geographical areas, argued that droughts during the Little Ice Age (LIA; ca. 14th to 19th centuries) might have affected the island's ecosystems and human practices leading to relevant cultural changes. However, evidence of such changes on the island was still lacking. Nunn (2007) proposed that Polynesian climates were relatively stable during the Medieval Climate Anomaly (MCA) but a phase of general instability and lower sea level started at AD 1300 and continued during the LIA, possibly caused by an intensification of the El Niño-Southern Oscillation (ENSO) variability. This climatic reversal would have led to widespread ecological and social crises in the region, and the cessation of transoceanic navigation. According to Nunn (2007), the cultural shift that represented the end of the ancient *moai*-building Rapanui society was a consequence of the LIA climatic deterioration but direct in situ evidence of climatic changes on the island remained to be demonstrated.

Azizi and Flenley (2008) studied sediments from Lake Raraku (Fig. 1) corresponding to the Last Glacial Maximum (LGM) and found palynological evidence of forest continuity, in spite of the presumed temperature and moisture declines. These authors concluded that if forests were resilient to climatic changes as intense as the LGM, further late glacial and Holocene environmental shifts of lower intensity could not have been responsible for the island's deforestation. This reinforced the view that the recent historical deforestation should have been anthropogenic, rather than of climatic origin. The influence of the ENSO variability was dismissed on the basis of instrumental records of the second half of the 20th century and modeling results showing that such interannual periodical forcing was unable to cause significant variations in precipitation patterns during the last millennium (Genz and Hunt 2003; Junk and Claussen 2011).

Climate changes

During the last two decades, paleoecological and paleoclimatic research on Easter Island has intensified and new sedimentary records have been obtained that provide new evidence for climatic changes during the last millennia. The first records suggesting the occurrence of arid climates during the Late Holocene came from Lake Raraku, in the coastal lowlands, and were used to tentatively relate aridity and ecological shifts, especially associated to forest dynamics (Mann et al. 2008; Sáez et al. 2009). Further work on the same lake yielded an almost continuous record for the last 2700 years that provided evidence for two drought phases, between ~AD 880 and 1170 and ~AD 1570 and 1720 (Cañellas-Boltà et al. 2013). The peats of the Rano Aroi swamp, in the interior uplands (Fig. 1), provided a continuous record of a similar time period showing three phases of landscape opening (i.e. forest retraction) associated to drier climates at 300 BC to AD 50, AD 600 to 1100, and AD 1520 to 1700 (Rull et al. 2015). The two later phases roughly coincided with the Lake Raraku droughts and occurred during the MCA and the LIA, respectively (Fig. 2).

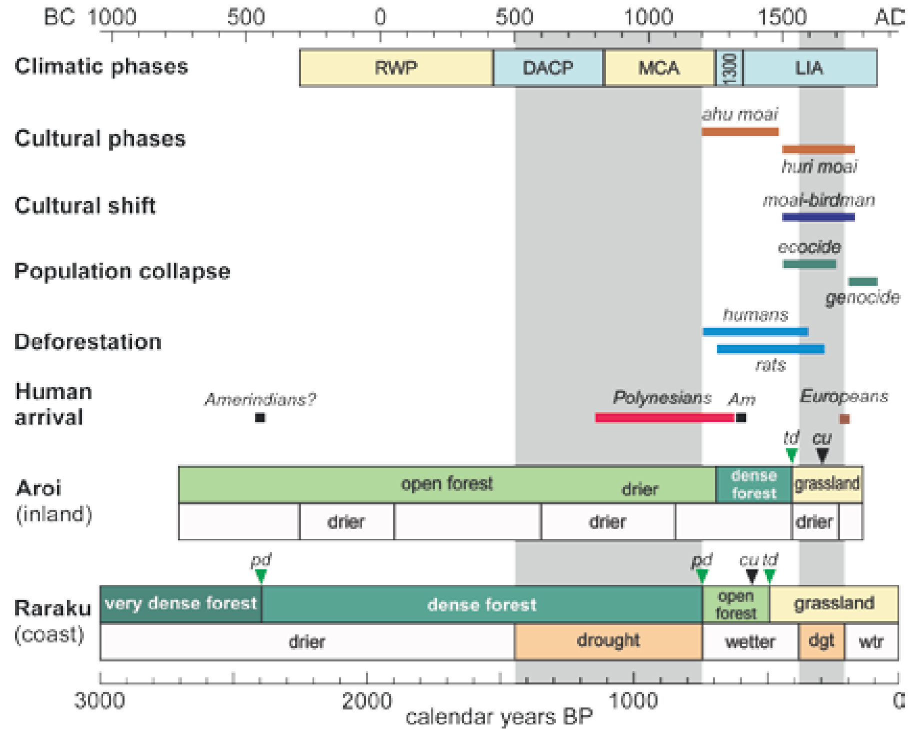

Figure 2: Summary of the climatic, ecological and cultural trends of Easter Island over the last three millennia (simplified from Rull et al. 2016). Drought phases are shaded. Horizontal bars represent the age range for the occurrence of the indicated cultural and environmental events, according to the available literature. Abbreviations: RWP = Roman Warm Period, DACP = Dark Ages Cold Period, MCA = Medieval Climate Anomaly, 1300 = "1300 event", LIA = Little Ice Age, Am = Americans, cu = first evidence of local cultivation, dgt = drought, pd = partial deforestation, td = total deforestation, wtr = wetter.

Deforestation

The Raraku and Aroi records showed heterogeneous deforestation patterns across the island. In Raraku, deforestation began by 450 BC and was associated with the onset of charcoal and the pollen of *Verbena litoralis*, a weed of American origin (Cañellas-Boltà et al. 2013). This challenged previous theories of a unique colonization event from Polynesia by AD 800-1200. However, this is not a direct evidence of human presence and should be confirmed with further studies. In addition, archaeological evidence for such an early colonization (BC 450) is still lacking. The deforestation of this catchment was completed by AD 1530 (Fig. 2); therefore, forest clearing was a slow and gradual process elapsing two millennia. The situation was very different in the Aroi catchment, where forests remained virtually untouched until AD 1520 and were rapidly removed in roughly one century. This deforestation coincided with the appearance and sudden increase of charcoal particles suggesting anthropogenic burning (Rull et al. 2015). Another difference between the Raraku and Aroi sites was that, prior to deforestation, the first was occupied by dense forests whereas the second was covered by open forests (Fig. 2). This has been explained in terms of altitudinal differences in the vegetation cover due to climatic constraints (Flenley and Bahn 2003), a hypothesis that has not been confirmed yet. In the Kao basin, the lack of a reliable chronology (Butler and Flenley 2010; Horrocks et al. 2013) complicates the interpretation, but the record showed the occurrence of two deforestation events, between AD 50 and 100, and AD 1350 and 1800 (Butler and Flenley 2010). Spatio-temporal differences in deforestation patterns agree with the apparent heterogeneity in land-use practices documented by archaeological evidence (Stevenson et al. 2015). The combined evidence obtained so far suggests a conspicuous pattern of coastal abandonment toward inland settlements, a common feature in many eastern Pacific archipelagos during the same times (Nunn 2007).

A new scenario

The concurrence of conspicuous climatic, ecological and cultural changes during the last millennia suggests that the recent history of Easter Island may be more complex than previously thought and that natural and anthropogenic drivers of change, as well as their potential synergies, might have been influential in determining cultural shifts (Rull et al. 2016). Rather than simplistic scenarios of single, simultaneous and island-wide cause-effect relationships, a holistic perspective that considers all the potential forcing factors should be pursued to explain Easter Island's landscape and cultural changes. Further research should be addressed under a new perspective including paleoecological, archaeological, anthropological and historical evidence. The incorporation of direct sedimentary evidence of human presence, such as fecal lipids or DNA, is strongly recommended (Rull et al. 2016).

AFFILIATIONS

[1]Institute of Earth Sciences Jaume Almera (ICTJA-CSIC), Barcelona, Spain
[2]Department of Prehistory, Ancient History and Archaeology, Universitat de Barcelona, Spain
[3]Ecological Research Center and Forestry Applications (CREAF), Cerdanyola del Vallès, Spain
[4]Department of Earth and Ocean Dynamics, Universitat de Barcelona, Spain

CONTACT

Valentí Rull: vrull@ictja.csic.es

REFERENCES

Azizi G, Flenley JR (2008) Quat Int 184: 166-176

Butler KR, Flenley JR (2010) Rapa Nui J 24: 5-10

Diamond JM (2005) Collapse: How Societies Choose to Fail or Succeed. Penguin, 608 pp

Cañellas-Boltà N et al. (2013) Quat Sci Rev 72: 36-48

Flenley JR, Bahn PG (2003) The Enigmas of Easter Island. Oxford University Press, 256 pp

Horrocks M et al. (2013) J Paleolimnol 50: 417-432

Genz J, Hunt TL (2003) Rapa Nui J 17: 7-17

Hunt TL (2007) J Archaeol Sci 34: 485-502

Junk C, Claussen M (2011) Clim Past 7: 579-586

Mann D et al. (2008) Quat Res 69: 16-28

McCall G (1993) Rapa Nui J 7: 65-70

Nunn PD (2007) Climate, Environment and Society in the Pacific During the Last Millennium. Elsevier, 316 pp

Rull V et al. (2015) Quat Sci Rev 126: 219-226

Rull V et al. (2016) Front Ecol Evol 4: 29, doi 10.3389/fevo.2016.00029

Sáez A et al. (2009) Quat Sci Rev 28: 2743-2759

Stevenson CM et al. (2015) PNAS 112: 1025-1030

Wilmshurst JM et al. (2011) PNAS 105: 7676-7680

doi: 10.22498/pages.24.2.72

Fires: the main human impact on past environments in Patagonia?

Andrés Holz[1], C. Méndez[2], L. Borrero[3], A. Prieto[4], F. Torrejón[5] and A. Maldonado[6]

Multidisciplinary research in fire dynamics in the Patagonian-Andean region is incipient. In this review, we synthesize archaeological, anthropological, paleo-, dendro- and neoecological projects on past climate-human-fire-vegetation dynamics to establish ecological benchmarks to burning over time.

Fire, one of the most ubiquitous disturbances on earth, is a key driver of ecosystem dynamics globally. Fire controls major boundary dynamics and even the distribution of certain biomes. Hominins have altered the geography and regimes of fires from ca. 1.5 million years ago (Parker et al. 2016), and, in turn, fire became a key tool for evolutionary history, through impacts on landscape and resources, and constraints on knowledge, inter-group competition and geography. This work reviews the potential impact of human-set fires, favored by climate conditions, on forests and grasslands since their first appearance in two Patagonian-Andean regions: the wetter western region, from the Pacific coast to the Andean peaks; and the drier eastern region, from the Andean peaks to the Atlantic coast (Fig. 1).

The role and sources of fire ignition in southern South America (SSA; south of ca. 38°S) have been long-debated. Some have ignored top-down climate factors and highlighted large-scale impacts of human-set fires (i.e. Heusser 1994), whereas others have preferred a perspective of fine-scale human impact favored by conducive climate-fire conditions (Markgraf and Anderson 1994; Holz and Veblen 2011a; Méndez et al. 2016). In Patagonia, fire was among the key tools for human groups for activities such as cooking, heating and hunting, as suggested by ethnographic sources. The archaeological records suggest that human occupation (and burning activity) was neither continuous nor homogenous over time and space (Fig. 1; 2e,f). The interpretation of the role of humans in setting fires in Patagonia is also a point of contention – some claim that first human appearances coincide with the onset of regional fire activity, others argue peaks in fire activity are only significant during periods when higher population densities were present throughout the landscape. For instance, at the northern margin of Patagonia, evidence of anthropogenic fire is documented from ca. 18.5-14.6 ka cal BP, the age of the earliest evidences of human settlement (i.e. Monte Verde at ca. 41°S; Dillehay et al. 2015), and reached southernmost Patagonia (ca. 52-55°S) at ca. 12.6 ka cal BP (Fig. 1).

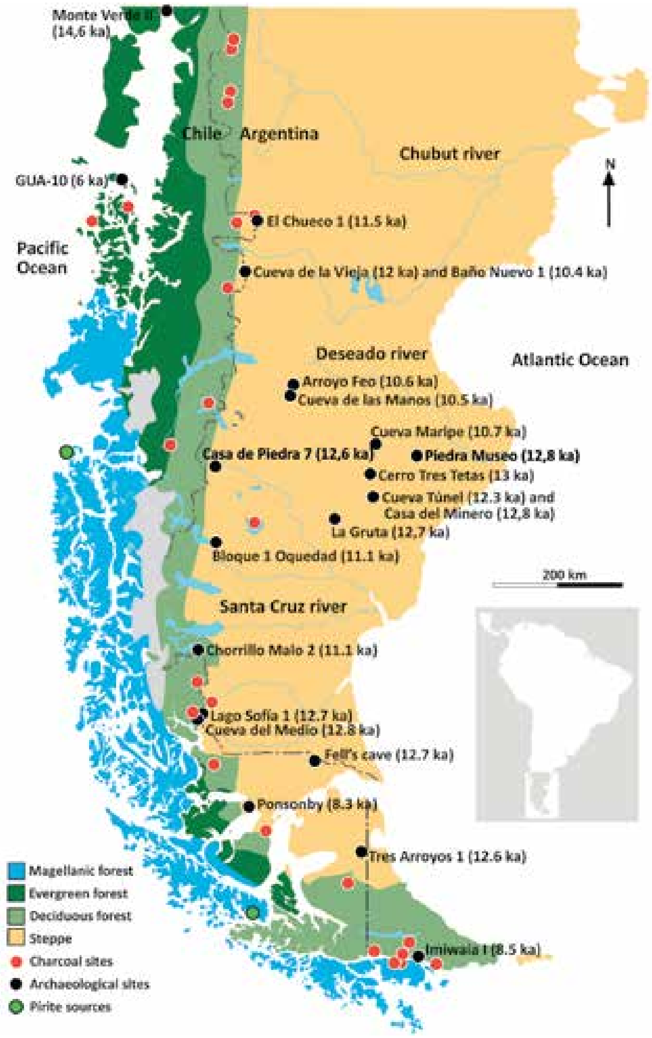

Figure 1: Location of regional earliest archaeological (calibrated ages BP in parenthesis) and paleoecological sites and main modern vegetation types cited in the text. The western and eastern Patagonian-Andean regions encompass the Magellanic and evergreen forests and deciduous forest and steppe, respectively.

From a top-down perspective, fire activity in Patagonia has been controlled by natural ignition, biomass accumulation and climate variability at multiple time scales: from millennial (e.g. summer insolation and westerly winds strength and position; Whitlock et al. 2007), centennial (i.e. location of subtropical pacific anticyclone, and westerly winds strength and position; Holz et al. 2012), to decadal and interannual scales (e.g. El Niño Southern Oscillation, ENSO; The Southern Annular Mode, SAM; Holz and Veblen 2011b). Under current climate conditions, fires occur during the Austral summer, and natural ignitions are relatively rare on the western Andean slope but common on the drier, eastern side of the Andes (Kitzberger et al. 2016).

Climate, fire, vegetation, and human occupation

In Patagonia, vegetation developed asynchronously across latitude and longitude, with broadly earliest establishment in Northern Patagonia, east of the Andes, and latest development in Southern Patagonia, west of the Andes. Wet/cool conditions were observed since the last glacial maximum and during the transition to the Holocene that favored establishment of initial forest taxa at ca. 16.5-13.5 ka BP in Northern Patagonia (ca. 37-44°S; Iglesias et al. 2016). In the early Holocene (ca. 11.5-8 ka BP), initial forest taxa established south of ca. 44°S (de Porras et al. 2012) under high El Niño (positive ENSO) activity, coinciding with drier conditions in Northern Patagonia, and wetter and warmer conditions in Central and Southern Patagonia, respectively (Fig. 2a-d). These conditions favored the highest peak in fire activity on record in Patagonia (Fig. 2e). During the Mid Holocene (ca. 8-4 ka BP), wet conditions in North and Central Patagonia coincided with a dry-to-humid transition in Southern Patagonia and low ENSO activity. Overall high climate variability was observed in the late Holocene (ca. 4 ka BP to present), with intermediate fire

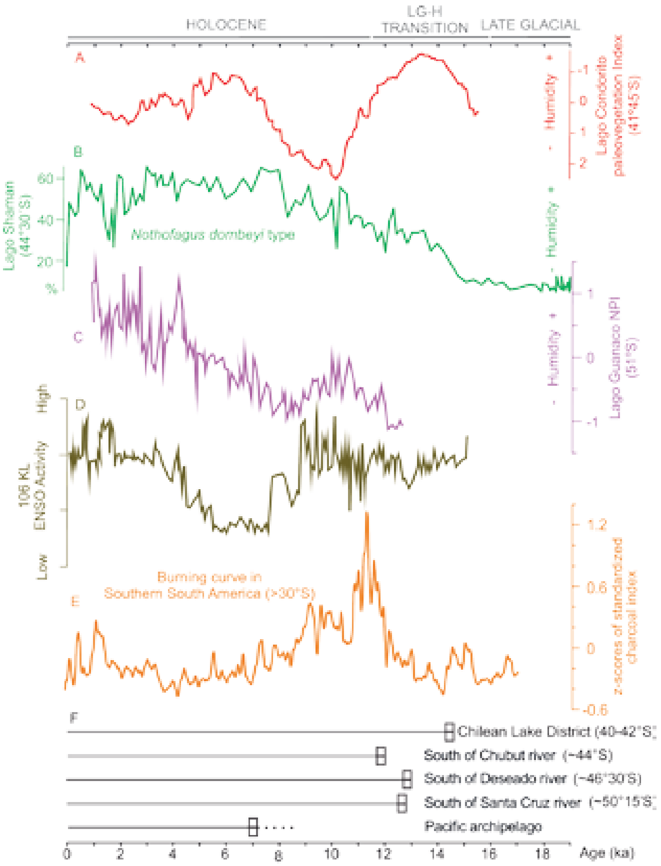

Figure 2: Changes in climate, fire and human occupation in southern South America over time. Pollen-based humidity paleo-indices for Northern **(A)**, Central **(B)**, and Southern **(C)** Patagonia. **(D)** Lithic flux rate (% of maximum; Marine core ENSO reconstruction at 12°S). **(E)** Burning curve in SSA (>30°S, smoothed with a 200-year window. **(F)** First-arrival dates based on earliest regional archaeological records.

activity that co-occurred with mid-to-high ENSO activity, drying conditions in Northern and Central Patagonia, and very humid conditions in Southern Patagonia – presumably due to a southward shift of the westerlies (rather than changes in human ignition or westerlies strength; Fig. 2a-e). Over the last several hundred years, fires occurred mainly during fire-prone phases of ENSO and SAM (Holz and Veblen 2011a).

In western Patagonia, fire records date back to ca. 11 ka BP (e.g. Holz et al. 2012), which precede human arrival (ca. Mid Holocene, Fig. 2f). In this region, the archaeological record is richest over the last two millennia (Reyes et al. 2015). At the time of first European contact (ca. late 1500s), indigenous groups practiced localized slash and burn agriculture (ca. 40-44°S). Further south in the channels, with cooler and wetter conditions, small canoeist groups lived off seal hunting, fishing and used pyrite for starting bonfires (Fig. 1). These groups were known to transport active bonfires in their canoes. Pyrite was also commonly used to burn small coastal temperate rainforest patches that were subsequently harvested for fuel. Starting in the mid-1750s, European-settlers burned vast extensions of native forests to facilitate access to coastal rainforest trees of valuable timber (Holz and Veblen 2011a). On the western Andean slopes, most tree species can neither resist nor recover following large, high severity events, which eliminate seed source. Some tree species, however (e.g. *Pilgerodendron*) can recover from sporadic, low-to-moderate fire severity events (Kitzberger et al. 2016).

Along the eastern Andean foothills, fires have been recorded as far back as ca. 17 ka BP (Iglesias et al. 2016), and precede human contact (Fig. 1, 2e,f). Tehuelche people set fires for smoke signaling and hunting – activities that vastly increased in the 18th century with the introduction of horses. Tehuelche people had higher demographic concentrations than coastal groups and were known for their series of bonfires burning in front of and inside their *toldos* (hide huts). Some of the dominant forest taxa in this region possess traits that allow them to resist fire (e.g. thick bark and self-pruned stem in Araucaria) and quickly re-establish following fires (e.g. sprouting capabilities in *Nothofagus antarctica*; Kitzberger et al. 2016).

Regional trends and multidisciplinary research in Patagonia

At the largest scale, fire in Patagonia appears to have been shaped by both climate conditions and human ignitions. Overall trends in fire activity correspond well with millennial-scale variability in moisture availability (Fig. 2). The highest fire peak on record, however, took place not long after first human contact across Patagonia, and hence cannot be explained by climate conditions alone. These big-picture results suggest that climate conditions control fire activity at large scales, but human ignitions were responsible for pulses in fires (as long as climate conditions were suitable for burning).

At this large scale, it is difficult to assess the relationship between demographic density and the impact of human-set fires. Instead, site-specific studies with multidisciplinary approaches seem more useful; e.g. archaeo-paleoecological paired work in the deciduous forest and steppe ecotone in Central Patagonia (44°S) found that human presence strongly correlate with fires throughout the Holocene, especially during periods of high fuel availability (i.e. wet periods; Fig. 1; Méndez et al. 2016). In the evergreen forest and peatland ecotone of western Patagonia (47°S), paired paleo-dendro-neoecological data with historical analyses indicate that indigenous fine-scale burning was common before European-settlers' arrival (Fig. 1; Holz and Veblen 2011a). Studies also indicate that 20th-century burning reached peaks up to four times higher than at any time during the Holocene (Holz et al. 2012) and has transformed the plant community into an alternative, more flammable vegetation state (Kitzberger et al. 2016). Studies conducted in similar biophysical settings in New Zealand suggest that relatively small groups of Maori people were able to burn and transform very large extensions of temperate forests ca. 0.8 ka BP because of vegetation flammability-fire feedbacks (Perry et al. 2012). We expect that ongoing multidisciplinary work will shed new light on the role that humans had on shaping past environments in Patagonia.

ACKNOWLEDGEMENTS

This research was supported by the US NSF (0966472), FONDECYT (1130128, 1130151, 1120765) and FONDAP CRHIAM (15130015).

AFFILIATIONS

[1] Department of Geography, Portland State University, Portland, USA
[2] Department of Anthropology, University of Chile, Santiago, Chile
[3] Instituto Multidisciplinario de Historia y Ciencias Humanas, Buenos Aires, Argentina
[4] Campus Natales, University of Magallanes, Punta Arenas, Chile
[5] Aquatic Systems Research Unit, University of Concepción, Chile
[6] Centro de Estudios Avanzados en Zonas Áridas, University of La Serena, Chile

CONTACT

Andrés Holz: andres.holz@pdx.edu

REFERENCES

de Porras ME et al. (2012) Quat Sci Rev 50: 71-85

Diaz MF et al. (2007) Forest Ecol Manag 244: 32-40

Dillehay TD et al. (2015) PLoS ONE 10, doi: 10.1371/journal.pone.0141923

Heusser CJ (1994) Rev Chil Hist Nat 67: 435-443

Holz A et al. (2012) Clim Past 8: 451-466

Holz A, Veblen TT (2011a) Palaeogeogr Palaeoclimatol Palaeoecol 311: 82-92

Holz A, Veblen TT (2011b) Geophys Res Lett 38, doi:10.1029/2011GL047674

Iglesias V et al. (2016) Palaeogeogr Palaeoclimatol Palaeoecol 457: 195-208

Kitzberger T et al. (2016) New Zeal J Bot 54: 247-272

Markgraf V, Anderson L (1994) Rev IG Sao Paulo 15: 33-47

Méndez C et al. (2016) Front Ecol Evol 4: doi: 10.3389/fevo.2016.00100

Parker CH et al. (2016) Evol Anthropol 25: 54-63

Perry GLW et al. (2012) Glob Change Biol 18: 1609-1621

Reyes O et al. (2015) J I Coast Archaeol 10: 207-231

Whitlock C et al. (2007) Quat Res 68: 28-36

doi: 10.22498/pages.24.2.74

DAPS - Paleoclimate Reanalyses, Data Assimilation and Proxy System modeling

Hugues Goosse[1], M. Evans[2] and S. Khatiwala[3]

The analysis of observations and numerical simulations are two key pillars of many scientific disciplines. Traditionally, a study is initially focused on one of these two aspects and the other one appears in a second stage, to test a hypothesis or validate a conclusion (Fig. 1). Data assimilation uses observations and simulations to produce estimates based on both sources of information, given uncertainties in each. If key assumptions within the approach are met, this approach allows estimation for regions and times which lack observations, leads to mechanistic analyses and re-evaluation of uncertainty estimates, and provides the rationale for new observational and modeling experiments.

Perhaps, particularly in paleoscience, combining the information deduced from simulations with that from observations may not be straightforward and a wide range of issues must be addressed before that is possible. For instance, the variable measured in environmental archives collected in the field (such as tree-ring width or pollen assemblage) may not be directly simulated by the model, it may map as a response to more than one environmental variation, and there is chronological uncertainty. Model results and observations thus have to be processed and interpreted appropriately before a quantitative evaluation of the agreements and inconsistencies between the two may be made. The spatial scales represented by the records and model results are generally also different and difficult to determine accurately. Additionally, both observational error and model biases need to be quantified to make a meaningful comparison, and new approaches to validation of the results and interpretations must be developed.

The goal of the new PAGES working group on Paleoclimate Reanalyses, Data Assimilation and Proxy System modeling (DAPS; http://pastglobalchanges.org/ini/wg/daps/intro) is to address these challenges. Specifically, DAPS is designed to stimulate the development of methods for the joint and quantitative use of observations and models in paleoscience, by promoting integrative research and mechanistic understanding of process and history by combining, as objectively as possible, all available sources of paleoenvironmental information.

Reanalyses are probably the most complete illustration of the approach. Using data assimilation techniques, they combine observations with a description of the dynamics of a system, as represented in a model, to reconstruct the state of this system, explicitly taking into account all the uncertainties in each. Observations and model are thus merged from the beginning of the process (Fig. 1). The quality of the product is linked to the quality of both sources of information but, even more crucially, their integration. This implies a deep understanding of not only data assimilation techniques and dynamics, but also the characteristics of the paleoclimate records and their uncertainties. This requires strong interaction between the different communities involved.

A critical step in the reanalysis is an objective model-data comparison. This implies the development and inclusion of "proxy system" models (e.g. Evans et al. 2013) for the paleoclimatic observations, so the measured variable can be directly assimilated into numerical simulations. Ideally, those proxy system models are based on a mechanistic understanding of the way the recorded signal arises from the external environmental conditions as simulated by the numerical model, then imprinted into an archive, and observed. Proxy system models may also be applied in standard simulations when model outputs are compared to observations.

Successful applications of proxy system models and data assimilation have been previously demonstrated (e.g. Dee et al. 2016). DAPS will review these and identify areas in which improvements can be achieved through synergies and coordination. Another important goal is to establish a code repository facilitating joint activities, and to encourage new users to develop applications and collaborations, particularly between groups that have traditionally not yet extensively interacted. The plan is to further these goals through workshops and training activities organized via DAPS, targeting both early-career and experienced scientists and those who may not be familiar with data assimilation techniques.

Join this initiative! Subscribe to the DAPS mailing list (http://listserv.unibe.ch/mailman/listinfo/daps.pages) to be informed about plans for workshops and training activities. Do not hesitate to contact the members of the steering committee with questions and suggestions.

AFFILIATIONS

[1]ELIC/TECLIM, Université catholique de Louvain, Belgium
[2]Department of Geology, University of Maryland, USA
[3]Department of Earth Sciences, University of Oxford, UK

CONTACT

Hugues Goosse: hugues.goosse@uclouvain.be

REFERENCES

Dee et al. (2016) J Adv Model Earth Sy 8: 1164-1179

Evans MN et al. (2013) Quat Sci Rev 76: 16-28

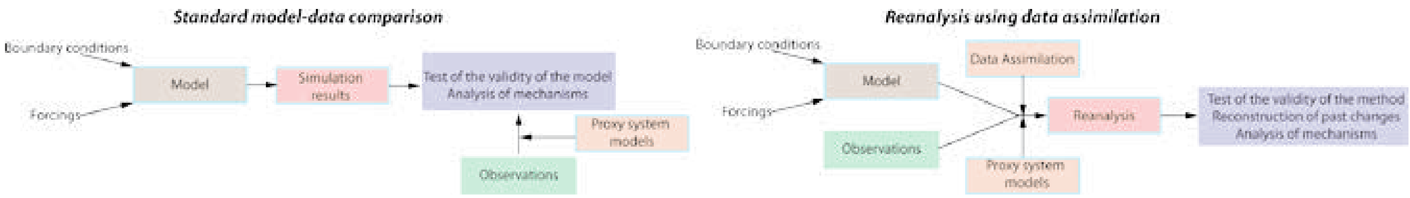

Figure 1: Schematic representation of a classical model-data comparison and of a reanalysis, illustrating in particular the role of proxy system models.

doi: 10.22498/pages.24.2.75

EcoRe3 - Resistance, Recovery and Resilience of Long-term Ecological Systems

Alistair W.R. Seddon[1], L.E. Cole[2], J. Morris[3], M. Shawn-Fletcher[4] and K.J. Willis[5]

"Resilience" is a key attribute needed to ensure the persistence of Earth's ecosystems in the face of increasing anthropogenic stressors and climate change. Yet definitions of resilience, and the methods used to measure it, can differ markedly between studies (Hodgson et al. 2015). These disagreements make it difficult to compare and identify systems with more or less resilience and to plan future mitigation strategies.

One useful approach is to integrate the different concepts of resilience within one unifying framework, by identifying the different "components" of resilience that lead to a system maintaining ecological functioning in the face of disturbance (Fig. 1). This is the first step for understanding what factors cause variations in resilience between different ecosystems. The next challenge is to develop tools to measure these components across biomes.

Recent attempts have used satellite data to map some components of resilience at global scales (e.g. Seddon et al. 2016). These "snapshots" are based on measuring short-term ecological responses, but whether the patterns reflect fundamental properties of the systems, or are the result of historical disturbance legacies, remains unknown. Sediments provide a long-term record of disturbances and ecological responses for investigating resilience (e.g. Cole et al. 2014), but the appropriate metrics for comparing components of resilience from sediments across different ecosystem types are yet to be developed.

Elasticity: Speed of recovery to equilibrium following a disturbance. Determines the recovery rate.

Precariousness: Distance to an ecological threshold or tipping point.

Latitude: Width of the basin (or ecological resilience, e.g. Holling 1973).

Resistance: Amount of change following a disturbance (in Fig. 1, basin with slope "a" has higher resistance than slope "b"; e.g. de Keersmaeker et al. 2015).

Sensitivity: Relative variance of system compared to driver (e.g. Seddon et al. 2016).

Box 1: Components of resilience - definitions

EcoRe3 is a new PAGES working group which aims to devise a set of standardized approaches for comparing components of resilience from the paleo-record. We focus on measuring resistance (the amount of change following a disturbance), recovery (the speed to return to equilibrium following a disturbance) and how these components contribute to the resilience (the ability to tolerate disturbance and remain in the same state) in ecological systems using long-term data.

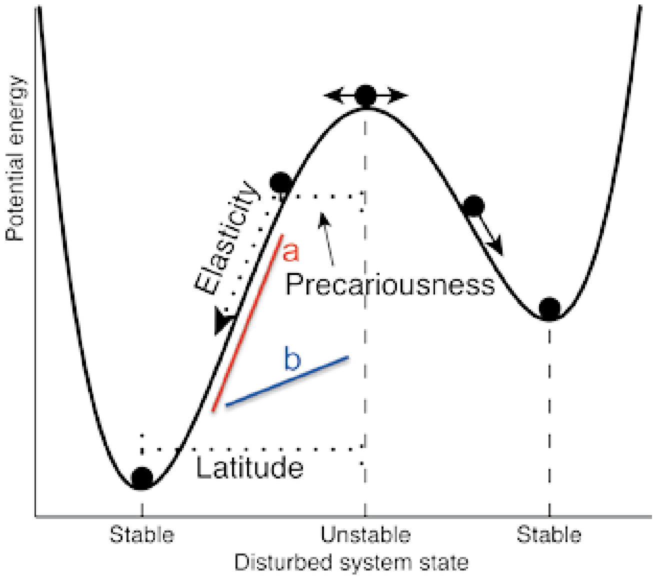

Figure 1: Components of resilience (adapted from Hodgson et al. 2015), showing a classical resilience landscape where components of resilience can be derived. See Box 1 for definitions.

Scientific objectives

EcoRe3 is based around four key scientific objectives:

Theory: We will develop methods, grounded in ecological theory, to measure and compare resistance, recovery and resilience using long-term ecological datasets. These will be explored at the first EcoRe3 workshop in March 2017 (www.pastglobalchanges.org/calendar/127-pages/1652-ecore3-1st-wshop-17).

Application: Using a series of high-resolution paleoecological records to test the use of these approaches will enable us to compare components of resilience across biomes, and investigate which biotic and abiotic controls are responsible for the observed patterns.

Training: Open-Source code will be developed for all analyses to ensure reproducibility of the methods. A workshop for early-career scientists, towards the end of the group's third year, is planned.

Integration: A major goal is to find ways to collaborate with scientists interested in resilience across different disciplines. In addition to working together with other PAGES working groups, we plan to investigate how to integrate the tools developed on paleo-datasets into those that can be used for the management of contemporary ecosystems.

For further information about EcoRe3 activities, please subscribe to the mailing list. http://pastglobalchanges.org/ini/wg/ecore3/

AFFILIATIONS

[1] Department of Biology, University of Bergen, Norway
[2] Department of Zoology, University of Oxford, UK
[3] Department of Geography, University of Utah, Salt Lake City, USA
[4] School of Geography, University of Melbourne, Australia
[5] Oxford University and Royal Botanic Gardens, Oxford, UK

CONTACT

Alistair Seddon: alistair.seddon@uib.no

REFERENCES

Cole LES et al. (2014) Nature Comm 5, doi:10.1038/ncomms4906

Hodgson D et al. (2015) Trends Ecol Evol 30: 503-506

Holling CS (1973) Annu Rev Ecol Evol Syst 4: 1-23

Seddon AWR et al. (2016) Nature 531: 229-232

doi: 10.22498/pages.24.2.76

A cross-disciplinary initiative to analyze past floods

Bruno Wilhelm[1] and Juan Antonio Ballesteros-Cánovas[2]

1st Floods Working Group meeting, Grenoble, France, 27-30 June 2016

PAGES' Floods Working Group (FWG) contributes to global knowledge of the variability of flood frequency and magnitude. The cross-disciplinary analysis of hydrological extreme events involves different temporal (from seasons to millennia) and spatial scales (regional to continental).

FWG's first workshop, involving 46 researchers from 16 countries (a third being early-career scientists), was the starting point to establish a community devoted to past and present floods and create links between paleoscientists, historians, statisticians, hydrologists and climatologists. The principal objectives were to share disciplinary experiences, promote interdisciplinary collaborations and design future projects and products for the group. Introductory keynote presentations were given before the sessions by N. Macdonald, S. St George, R. Denniston, M. Macklin, B. Valero Garcès, L. Schulte and M. Mudelsee.

The first session reviewed the different archives (i.e. sedimentary, speleothem, tree-ring and historical) and their suitability to document past flood occurrences and magnitude, with a particular focus on their respective advantages and limitations. This unprecedented systematic overview of all types of flood archives motivated participants and generated cross-disciplinary debates. The benefit of gathering flood data provided by different archives and methods was considered as great because of the wealth of information provided in term of data diversity and quantity for further analysis on flood variability.

The second session highlighted the potential for multi-archive flood approaches to get more precise and complete regional flood knowledge, including calibration of flood records with instrumental data. Participants pointed out opportunities and challenges to handle flood archives with different time resolutions. This should be the target of an interdisciplinary group project, with researchers from different fields collaborating towards a common understanding of past flood activity and exploring the possibility to integrate data of a different type within a unique dataset.

The last session was dedicated to statistical and modeling tools that could be applied to flood reconstructions to analyze flood patterns and identify responsible climate forcing. Particular emphasis was placed on the statistical comparison of archive data with instrumental records for flood hazard assessment. In the discussions following this session, the group identified the need to involve more climate modelers, hydrologists and risk managers to improve the understanding of the physical processes controlling the occurrence and magnitude of floods. These scientific collaborations and synergies could help to contribute to the present debate about floods-climate-human linkages and interactions.

Time was also dedicated to sub-group and plenary discussions on three specific topics: (i) the creation of a metadatabase of past flood events, (ii) the need to communicate the archive-based flood data to other communities, and (iii) collaborative efforts within the FWG. Based on a consensus, FWG's next steps will be the creation of this metadatabase, gathering published data, followed by its analysis in a review paper. The metadata collection will be done by groups, each focusing on a specific type of archive. First, each group will identify the archive type-specific selection criteria for metadata collection and a set of common criteria will then be defined. Once this first database version is finalized, a format for the inclusion of the actual data will be defined and the data collection planned. The format for the database will build upon the work of other PAGES working groups (e.g. McKay and Emile-Geay 2016). Deadlines for these three steps were established in order to deliver the first metadatabase version at the PAGES OSM in Zaragoza (9-13 May 2017), where the next FWG meeting and the FWG-sponsored session "Multidisciplinary reconstruction of paleofloods" will take place.

Post-workshop materials (report, keynotes, talks and posters) are available here:

www.pastglobalchanges.org/calendar/127-pages/1553-cross-community-workshop-on-past-flood-variability

Figure 1: September 2014 flood event in Kashmir valley (India) leading to the complete submersion of houses of the largest city, Srinagar, during several days (National Disaster Response Force - NDRF).

ACKNOWLEDGEMENTS
The workshop has been generously supported by PAGES, Labex OSUG@2020 (Investissements d'avenir – ANR10 LABX56), European Geosciences Union, Grenoble-INP and Université Grenoble Alpes.

AFFILIATIONS
[1]LTHE, University Grenoble Alpes (CNRS, IRD), Grenoble, France
[2]Environmental Science, University of Geneva, Switzerland

CONTACT
Name: bruno.wilhelm@ujf-grenoble.fr

REFERENCE

McKay NP, Emile-Geay J (2016) Clim Past 12: 1093-1100

doi: 10.22498/pages.24.2.77

PlioVAR marine synthesis update meeting

Erin L. McClymont[1], A.M. Haywood[2], P. Dekens[3], A. Rosell-Melé[4] and L. Dupont[5]

Utrecht, The Netherlands, 2 September 2016

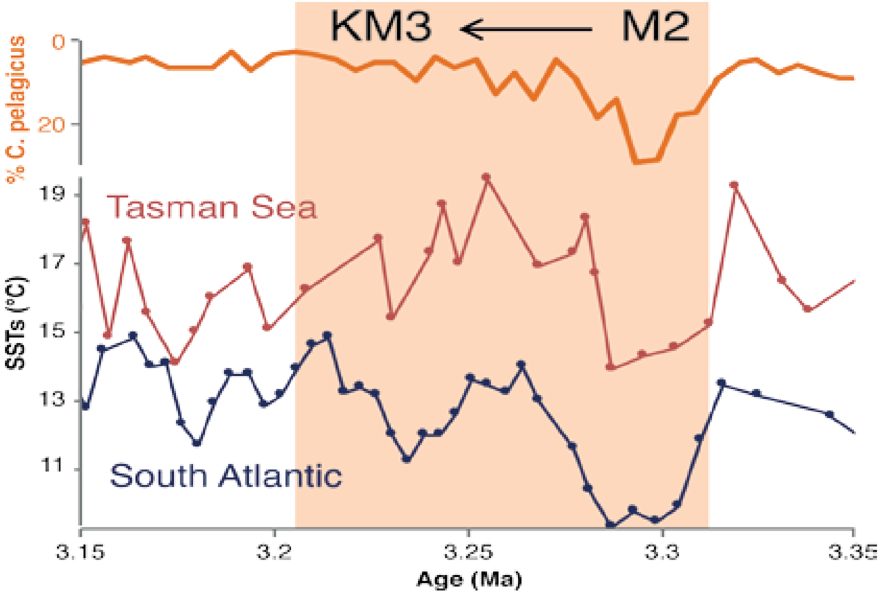

Figure 1: An example of data synthesis and comparison for the M2-KM3 transition from three southern hemisphere records: abundance of coccoliths from Coccolithus pelagicus at ODP Site 1172 (east of Tasmania; Ballegeer et al. 2012), and reconstructed sea-surface temperatures (SSTs) from DSDP Site 593 (Tasman Sea; McClymont et al. 2016) and ODP Site 1090 (Southern Atlantic; Martinez-Garcia et al. 2010).

Following the International Conference on Paleoceanography in Utrecht, 40 members of the PlioVAR working group met to receive and discuss progress reports on synthesis work of existing and emerging multi-proxy marine data during the late Pliocene. Participants working with marine proxies and with varied regional interests were present, as well as those with previous experience in large paleoclimate syntheses. Six presentations were given, with the first outlining the aims and objectives of PlioVAR. The other five reported on the developing syntheses from the North Atlantic, South Atlantic, Pacific, Indian and Southern Oceans. An open discussion then considered the implications of the work so far, alongside future strategies to support continued synthesis. The questions and priorities identified during the meeting include:

1. Regional differences emerging in glacial-interglacial variability

A target of PlioVAR is to assess the magnitude and rate of climate changes associated with the "M2-KM3" event, marked by ice-sheet expansion and then retreat around 3.3-3.2 Ma BP (Fig. 1). This climate transition was identified in many of the existing records, but its amplitude varied depending on local circulation (e.g. upwelling, proximity to fronts), water mass and the proxy used. The importance of setting the late Pliocene variability in the context of Pliocene-Pleistocene climate evolution was noted, and the potential to examine shorter timescale variability was outlined. Variations in dust supply and glacial inputs to marine sediments were also noted as potentially valuable indicators of atmospheric circulation, environmental change onshore and ice-sheet behavior.

2.Reconciling environmental signals from multi-proxy analyses

A key aim of PlioVAR is to draw together multi-proxy perspectives on climate and environmental variability. Discussion about the signals recorded by different temperature proxy records emphasized the importance of detailing proxy measurements and interpretations in both the original publications and in the PlioVAR synthesis. These issues are not unique to PlioVAR but the working group is mindful of the implications, especially for planned data-model intercomparison.

3. New insights expected from recent and planned ocean drilling

Several recent IODP expeditions have secured new archives which have great potential to contribute to the PlioVAR initiative, in areas where data is currently limited or absent (e.g. Exp 353 Indian Monsoon, Exp 354 Bengal Fan, Exp 355 Arabian Sea Monsoon, Exp 356 Indonesian Throughflow, Exp 361 Southern African Climates). Several members of the science parties for these expeditions were present, and future plans and preliminary data were noted.

4. Management and integration of published and emerging data

Several presentations outlined the challenges of identifying and downloading existing data for incorporation into the synthesis, particularly due to missing information about stratigraphy, proxy calibrations and interpretations, as well as data not being available post-publication. Recommendations for data formatting and upload were discussed, with a need for metadata (e.g. which calibration was applied, IODP sample identifiers plus depth scales, original not just calibrated data provided). Ongoing efforts to create a protocol for assessing the quality of the age control were noted. Several possible means of creating an interface to view and download available data were presented, and their potential will be explored further.

Several conference sessions with a PlioVAR focus are scheduled, for example at the AGU Fall Meeting (2016) and PAGES Open Science Meeting (2017). Anyone interested in contributing to PlioVAR is encouraged to participate. The next PlioVAR meeting (19-21 April 2017, in Durham, UK; www.pastglobalchanges.org/calendar/127-pages/1658-pliovar-wshop-apr-17) will take place shortly before the PAGES OSM to focus on advancing the marine synthesis efforts outlined here. More information will be transmitted through the PAGES website and via the working group mailing list (www.pastglobalchanges.org/ini/wg/pliovar/).

We thank PAGES for the funding support which made this meeting possible.

AFFILIATIONS
[1]School of Geography, Durham University, UK
[2]School of Earth & Environment, University of Leeds, UK
[3]Department of Geosciences, San Francisco State University, USA
[4]ICREA and Universitat Autònoma de Barcelona, Spain
[5]MARUM - Center for Marine Environmental Sciences, University of Bremen, Germany

CONTACT
Erin McClymont: erin.mcclymont@durham.ac.uk

REFERENCES

Ballegeer A-M et al. (2012) Palaeogeog Palaeoclimatol Palaeoecol 313-314: 215-224

Martinez-Garcia A et al. (2010) Science 328: 1550-1553

McClymont EL et al. (2016) Paleoceanography 31: 895-913

doi: 10.22498/pages.24.2.78

Interdisciplinary views on the impacts of volcanic eruptions: from global to personal

Matthew Toohey[1], F. Ludlow[2], A. LeGrande[3], K.J. Anchukaitis[4] and M. Sigl[5]

VICS workshop, Palisades, USA, 6-8 June 2016

The inaugural workshop of the PAGES Volcanic Impacts on Climate and Society (VICS) working group convened approximately 50 established and early-career researchers from across Europe, North America, South America and Asia. Attendees, representing a wide range of research fields, presented on topics grouped into three broad themes: reconstructing volcanic activity and climate forcing through time, climatic responses to volcanic eruptions, and societal resilience and vulnerability to volcanically induced climate change. Discussion sessions focusing on key cross-cutting scientific questions were held to stimulate brainstorming of potential products for the working group.

Figure 1: Seventeenth century painting (oil on canvas) of Vesuvius erupting in AD 1631, by Domenico Gargiulo, depicting a religious procession (foreground) to secure divine deliverance from the eruption. Saint Januarius (San Gennaro) is also depicted flying above the procession (top foreground) in the direction of the mountain (Cocco 2013). Image from Wikimedia Commons in the public domain.

The importance of well-dated and accurate reconstructions of past volcanic activity was repeatedly acknowledged throughout the workshop. Ice cores provide perhaps the most complete record of global volcanism, with recently compiled and re-dated sulfate records allowing an estimation of the timing and magnitude of volcanic forcing back to 500 BC (Sigl et al. 2015), an advance that several attendees employed to refine our understanding of volcanic climatic and societal impacts. Developments were also showcased in the analysis of tephra particles in ice cores that allow volcanic sulfur signals to be traced to their source volcano, providing a link to the vast geological databases of volcanic eruptions. Attendees examined the challenges of translating proxies of past volcanism into knowledge of the associated radiative forcing, and highlighted the knowledge gained from the observation and modeling of recent, well-observed eruptions. Ongoing improvements in our ability to measure the isotopic signature of volcanic sulfur were also examined for their potential to reduce uncertainties in the radiative forcing inferred from the ice-core sulfate record.

Improvements in the spatial and temporal coverage and resolution of climate proxy records are allowing researchers to assess the impact of past volcanism on climate with increasing confidence. Speakers presented volcanic signatures in tree rings, speleothems, corals, glaciers and other proxies which reflect both the general global cooling that results from volcanic stratospheric aerosols, but also changes in atmospheric circulation and precipitation, including significant changes in monsoon-dependent agricultural regions now home to over 70% of the Earth's population. Recent work on the 1815 eruption of Tambora suggests that the main contributor to the cold and wet conditions in Switzerland was changes in atmospheric circulation, not the decrease in solar radiation from aerosol backscattering (Brönnimann and Krämer 2016). There are hints that expected circulation responses to volcanic forcing, such as the "winter warming" pattern over the Northern Hemisphere continents, can in fact be reproduced by climate models, but remaining notable discrepancies between simulated and reconstructed post-volcanic anomalies were highlighted. Speakers presented ongoing efforts to address such discrepancies through improved implementation of volcanic eruptions across climate models, and through collaborative standardized model experiments (Zanchettin et al. 2016).

Historical sources are increasingly recognized as providing valid paleo-climatic data at high spatial and temporal resolutions to complement instrumental records, tree-rings and other proxies (e.g. Gao et al. 2016). Of societal responses, historical sources are revealing not only of the immediate landscape and social impacts of eruptions (Fig. 1), but also how past societies coped with abrupt volcanically induced climatic shocks. Workshop participants thus presented societal-impact case studies from locations ranging from the far north, where agricultural societies were very susceptible to changes in summer temperature, to the tropics, where variations in the monsoons or river runoff had major agricultural impacts. These studies show how historians have rapidly incorporated recent advances in volcanic-forcing histories, and signaled that much more can be learned. Societies were not vulnerable in the same way in different seasons, for example, and the seasonality and scale of volcanic climatic impacts may differ with the location and timing of eruptions. Further advances can thus be achieved by closer dialogue between climate scientists, historians and other scholars of the human past.

ACKNOWLEDGEMENTS

We thank PAGES, the Climate Center of the Lamont-Doherty Earth Observatory and NASA Goddard Institute for Space Studies, and the Yale Climate History Initiative for financial support.

AFFILIATIONS

[1]GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
[2]Department of History, Trinity College Dublin, Ireland
[3]NASA Goddard Institute for Space Studies, New York, USA
[4]School of Geography and Development, and Laboratory of Tree-Ring Research, University of Arizona, Tucson, USA
[5]Paul Scherrer Institute, Villigen, Switzerland

CONTACT

Matthew Toohey: mtoohey@geomar.de

REFERENCES

Brönnimann S, Krämer D (2016) Geogr Bern G90, doi: 10.4480/GB2016.G90.01

Gao C et al. (2016) Quat Int 394: 180-193

Cocco S (2013) Watching Vesuvius: A history of science and culture in Early Modern Italy. University of Chicago Press, 336 pp

Sigl M et al. (2015) Nature 523: 543-549

Zanchettin D et al. (2016) Geosci Model Dev 9: 2701-2719

doi: 10.22498/pages.24.2.79

Fire, climate and biomes – towards a better understanding of this complex relationship

Anne-Laure Daniau[1] and Tim Brücher[2]

Global Paleofire Working Group 2 workshop, Beguey, France, 25-29 September 2016

The Global Paleofire Working Group phase 2 (GPWG2) is extending its focus to address linkages between fire and climate-driven fuel changes, traditional and modern human land-use management and biodiversity conservation issues. Thirty-two researchers from 11 countries with expertise in paleofire, biogeography and fire ecology, paleoclimate, expert assessment, and climate and fire modeling participated in this first meeting.

In recent years, variations in past fire activity have been mainly described by compositing fire signals geographically over large areas with heterogeneous vegetation or even climate-driven vegetation shifts. In contrast to that, the key purpose of this workshop, titled "Fire history baselines by biome", was to reconstruct fire activity based on vegetation patterns. We identified several approaches for such comparisons and discussed concepts based on regions with an underlying homogeneous vegetation (i.e. biomes; Fig. 1). These approaches range from testing fire vs. biome modeling to the study of fire traits, i.e. interactions between plants and fire that are explicitly described by a set of fire-specific plant functions. Ideas also emerged to investigate deviations from a "baseline" as past reference characteristics of a fire regime within a certain ecosystem (under stable-state conditions).

Model-data comparison based on the forthcoming FireMIP experiments offers another opportunity to better understand fire-vegetation interactions in the Earth system. In this regard, discussions focused on Last Glacial Maximum (LGM) to present comparisons, the experimental design, and on challenges in model-data comparison. The latter point related to the reduced number of sites for LGM to compare with and the interpretation of the time series within the Global Charcoal Database given as normalized trends. Such relative changes in past fire regimes limit the messages and possibilities that can be drawn out of these model-data comparisons.

Many of the discussions stressed the importance of calibration studies to obtain quantified and precise reconstructions of past fire regime metrics (fire size, intensity, frequency, etc.). GPWG2 launched a calibration initiative to build a "modern Global Charcoal Database", which will provide the possibility to analyze fire activity based on absolute numbers and a uniform and consistent set of charcoal units. This will allow a better interpretation and detailed intercomparison of charcoal records. Furthermore, upcoming model-data studies based on quantifiable variations in fire activity (i.e. fire regime metrics) will be possible. During the meeting, the next steps of this calibration endeavor were addressed and preliminary results suggest that calibration is possible when field, laboratory and analysis methods are consistent.

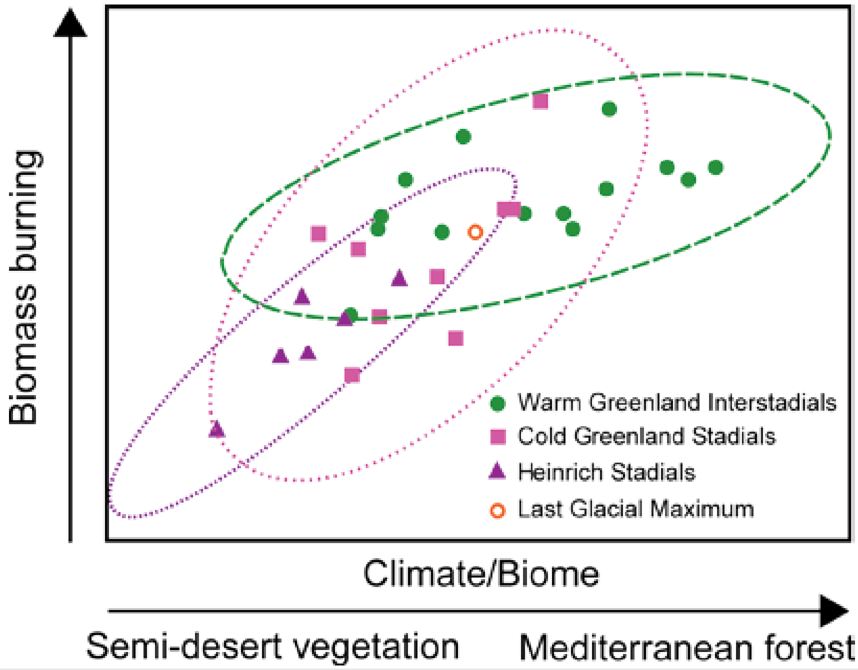

Figure 1: Fire-vegetation-climate interaction during abrupt climate change of the last glacial period in the Mediterranean region (modified from Daniau et al. 2010). During cold periods (Greenland and Heinrich Stadials), the dominant vegetation was characterized by semi-desert vegetation. The fuel-limited environment restricted biomass burning activity. The increase of regional temperature and humidity at the time of warm periods (Greenland Interstadial) led to a fire regime and vegetation shift towards increased biomass burning.

General statements on the risk of fires and the change of fire-danger indices in the IPCC indicate that both seem to increase under global warming. However, these indices are built upon simple assumptions rather than on detailed model analysis using dynamical vegetation–fire models including the interaction of all feedbacks (like fuel productivity influenced by the atmospheric CO2 fertilization). To propose a better evaluation for the next IPCC report, the workshop participants designed an expert assessment survey on the likelihood of future fire regime change for different climate-change scenarios. This assessment will focus on different Representative Concentration Pathways climate scenarios and compile the expert knowledge of modelers, field researchers and paleo-fire experts about the most relevant factors influencing fire regime in a particular region at different timescales.

The workshop also fostered connections between GPWG2 and two INQUA International Focus Groups – ACER and FBI-HYD. The development of a chronologically harmonized dataset of pollen and charcoal for the last glacial period (ACER) will allow analyses of fire-vegetation interactions in response to abrupt climate change (Fig. 1), and the cooperation with FBI-HYD, which examines fire-hydrology linkages in southern Africa, will expand the possibility of integrating the hydrological balance into vegetation-fire modeling in subtropical regions.

ACKNOWLEDGEMENTS

PAGES, PICS CNRS 06484 project, CNRS-INSU, Région Nouvelle-Aquitaine, University of Bordeaux DRI and INQUA are acknowledged for workshop support.

AFFILIATIONS

[1]Environnements et Paléoenvironnements Océaniques et Continentaux, CNRS-University of Bordeaux, Pessac, France
[2]Helmholtz Centre for Ocean Research, GEOMAR, Kiel, Germany

CONTACT

Anne-Laure Daniau: al.daniau@epoc.u-bordeaux1.fr

REFERENCE

Daniau AL et al. (2010) PLoS ONE 5, doi: 10.1371/journal.pone.0009157

doi: 10.22498/pages.24.2.80

Sea-level budgets at decadal to millennial timescales to bridge paleo and instrumental records

Heather D. Bervid[1], A. Glueder[1], E.A. Steponaitis[2] and A.G. Yanchilina[3]

PALSEA2 workshop, Mt. Hood, USA, 19-21 September 2016

The PALeo constraints on SEA level rise 2 (PALSEA2) working group recently convened for its fourth meeting, hosted by Oregon State University, at Timberline Lodge on Mt. Hood. This meeting focused on constraining sea-level budgets at decadal to millennial timescales in an effort to connect modern-instrumental and paleo sea-level records. Presentations addressed recent findings in terrestrial and marine sediment records, ice-sheet and ocean models, data analysis, and methods of linking modern sea-level observations with the paleo record.

Sea-level change since the Little Ice Age is preserved and widely studied in saltwater marshes. Saltwater marshes have potential to provide a biostratigraphic mechanism (using diatom assemblages) for linking past sea-level change data with instrumental observations to create a continuous record of Late Holocene sea-level change, and offer valuable near-, intermediate-, and far-field records of ice-sheet influence on sea level. However, the uncertainties associated with marsh records, including compaction and tidal range, must be taken into consideration when using these records to constrain ice-sheet sources. While existing global marsh records make up an extensive database of sea-level change (Fig. 1a), regions outside the northern Atlantic basin are understudied. This large data gap emphasizes the need for future field efforts in the Southern Hemisphere and the Pacific basin.

Uncertainties in current global sea-level records highlight the need to close the sea-level budget since the Last Glacial Maximum (LGM) and account for 4-32 m of missing ice and water (Fig. 1b). These uncertainties in the sea-level budget result from incomplete understanding of the system and are thus perpetuated by incomplete models of parameters such as ocean density, transient processes of ice sheets, global isostatic adjustment, dynamic topography and mantle rheology, groundwater and surface water systems, and land processes. Time periods in Earth history, including Marine Isotope Stage 3 (MIS 3), are also understudied, resulting in disagreement of sea-level reconstruction in the order of ~40 m between different records, and require more attention in the research community. Presentations on the complexity of this problem showed that the success of various global isostatic adjustments and earth models is largely dependent on choosing the right model for a specific research question to a specific region.

While datasets on Holocene paleoclimate and sea-level change are extensive, there is a need to compile these datasets into an open-access, intuitive database to spatially and temporally link these records at global and local levels. An ideal database would include all significant metadata, allowing researchers to improve upon dating techniques and standardize methods of data and statistical analysis. As it stands, there are significant uncertainties and inconsistencies between research groups in dating and modeling sea-level change, highlighting the need for incremental improvements of these methods within the paleoclimate community.

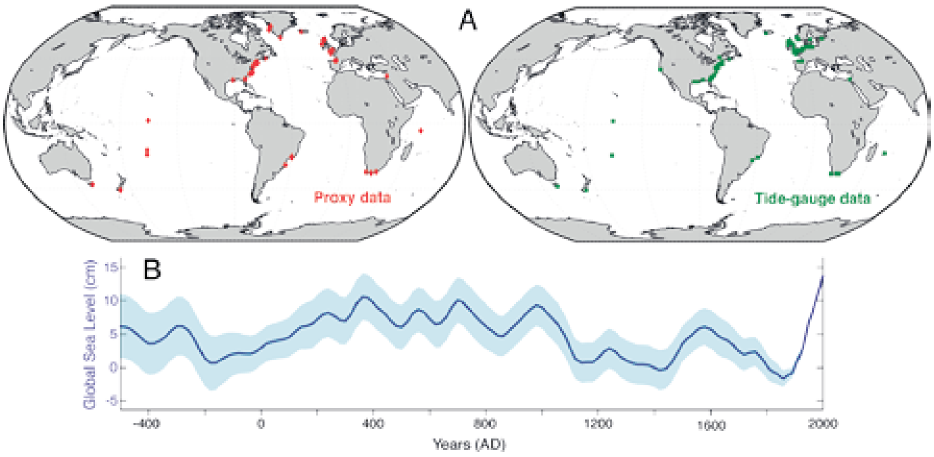

Figure 1: (A) Global distribution of paleoclimate proxy and modern tidal gauge sites, and **(B)** reconstruction of late Holocene sea-level changes (from Kopp et al. 2016; Copyright, 2016, National Academy of Sciences). Shading gives the 67% credible interval.

In the final discussion, there was a consensus that research on sea-level change could benefit significantly from collaboration with experts in other fields. Future work with Earth-system modelers, statisticians, and geophysicists who have an interest in paleoclimate studies, is necessary to address critical questions in glacial isostatic adjustment modeling, geochronology, database compilation, and data analysis. These collaborations would help better understand a system that has important implications for monitoring ongoing (and predict future) global sea-level change, and, ultimately, to make more robust predictions on the effect of climate change on local and global sea level. For the final phase of the working group, PALSEA2 will reconvene in 2017 with a focus on the phasing of sea-level and ice-sheet responses to climate change, and the processes and timescales which govern these responses.

ACKNOWLEDGEMENTS

Funding was provided by PAGES, INQUA, Oregon State University and the University of Florida. Thanks to the local hosts – Anders Carlson, his research group, and the staff at Timberline Lodge for their efforts.

AFFILIATIONS

[1]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, USA
[2]Department of Earth and Environmental Sciences, Tulane University, New Orleans, USA
[3]Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot, Israel

CONTACT

Heather Bervid: bervidh@oregonstate.edu

REFERENCE

Kopp et al. (2014) PNAS 113, doi: 10.1073/pnas.1517056113

doi: 10.22498/pages.24.2.81

Uncovering the past: multidisciplinary research on historic land cover and land use

Kees Klein Goldewijk[1], M.-J. Gaillard[2], K. Morrison[3], M. Madella[4] and N. Whitehouse[5]

LandCover6k general meeting, Utrecht, The Netherlands, 14-16 June 2016

The LandCover6k working group brought together a group of 50 scientists from various disciplines (archaeology, history, geography, paleoecology, land-use and climate modeling) to discuss progress and future plans to improve historical land-use descriptions for Holocene climate modeling. It was the group's second general workshop - the first being the launch meeting in October 2015 (Gaillard et al. 2015). Alongside this, a first workshop of the historians and archaeologists group was held in 2015 (Morrison et al. 2016) and several regional workshops have also been organized. The aim of this second general workshop was to update the group on the progress made during the working group's first year of activities, and plan the next steps.

LandCover6k's rationale is that adequate incorporation of land cover in global and regional climate models is not satisfactory, and the effect of anthropogenic activities on global climate via bio-geochemical and bio-geophysical processes in the past is not yet fully understood (www.pastglobalchanges.org/ini/wg/landcover6k).

An overview of modeled Holocene land-use changes was presented, based on a new version of the HYDE database (Klein Goldewijk et al. 2011) - updated with better data, irrigated and rain-fed cropland areas, and a distinction between managed pasture and extensive rangelands. The group reviewed patterns of HYDE, and regional comparisons were made with maps from historical geographers and archaeologists. One of the conclusions was that global allocation rules of HYDE do not perform well in the deep past due to a Eurocentric view of how people engaged in settlement and agriculture (expansion). Input from archaeologists and historians is clearly essential to this work and progress has already been made in southern and Central America, western Africa (see Fig. 1) and southern India. These regions are used as test cases of the land-use classification proposed by the LandCover6k working group (Morrison et al. 2016).

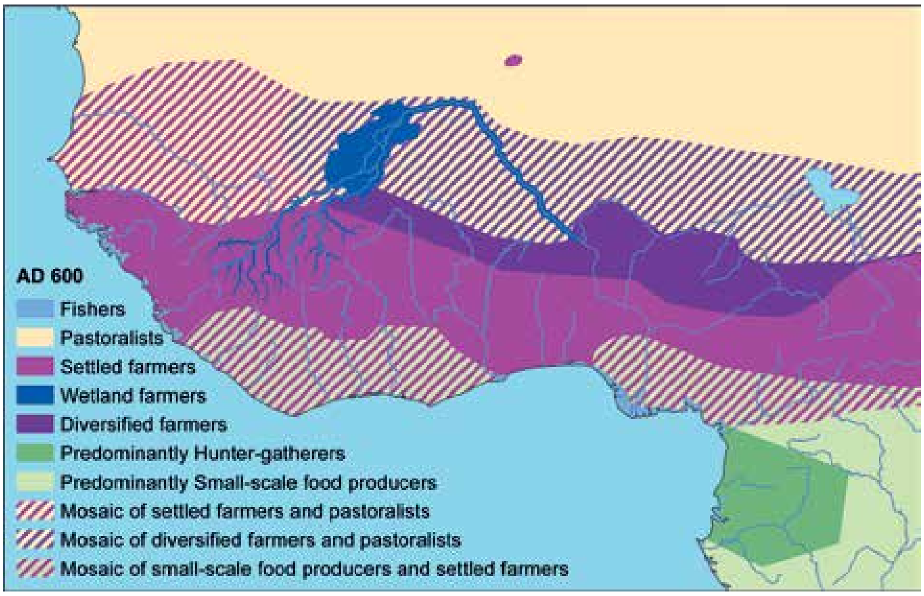

Figure 1: Livelihood distribution map for western Africa, AD 600 (Kay et al., unpublished data).

The group also reviewed progress made over the globe on regional pollen-based reconstructions of land cover) based on studies with the REVEALS model (Sugita 2007). REVEALS reconstructions for Europe except the Mediterranean and easternmost regions are already published (Trondman et al. 2015). REVEALS reconstructions will be available at the end of 2016 for parts of northern America, northern and temperate China, Siberia, and Cameroon.

Finally, current climate-modeling projects (e.g. within PMIP and CMIP) were reviewed and their needs in terms of past land-use and land-cover characteristics were discussed in the context of LandCover6k's aims and goals.

Participants agreed that focus should be on testing the global scale land-use categorization established by the archaeologists involved in LandCover6k in southern America and southern India, and on the pollen-based reconstructions in regions where they are achievable within the relatively near future, i.e. northern America, southern and eastern Europe, Siberia, and India. Moreover, a case study is planned to incorporate empirical archaeological data from a single region into the HYDE system, in order to see whether this would produce a significant difference in modeled past agricultural patterns, and to evaluate whether that difference would significantly impact on climate change. It was also decided that Neotoma (www.neotomadb.org) will act as the major archive of all case studies from LandCover6k.

The LandCover6k working group will continue to be present at many international conferences, organizing sessions and presenting scientific results. Forthcoming events are the European Geosciences Union Assembly 2017, and PAGES' 5th Open Science Meeting (OSM). The third general workshop of LandCover6k will be held in conjunction with the OSM on 16-17 May 2017 in Zaragoza, Spain. For more details, see: http://www.pastglobalchanges.org/calendar/127-pages/1637-landcover6k-wshop-2017

AFFILIATIONS

[1] Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands
[2] Department of Biology and Environmental Science, Linnaeus University, Kalmar, Sweden
[3] Department of Anthropology, University of Pennsylvania and the Museum of Archaeology and Anthropology, Philadelphia, USA
[4] Department of Humanities and ICREA, Universitat Pompeu Fabra, Barcelona, Spain
[5] School of Geography, Earth and Environmental Sciences, Plymouth University, UK

CONTACT

Kees Klein Goldewijk: c.g.m.kleingoldewijk@uu.nl

REFERENCES

Gaillard M-J et al. (2010) Clim Past 6: 483-499

Gaillard M-J et al. (2015) PAGES Mag 23: 81

Klein Goldewijk K et al. (2011) Glob Ecol Biogeogr 20: 73-86

Morrison K et al. (2016) PAGES Mag 24: 40

Sugita S (2007) Holocene 17: 229-241

Trondman A-K et al. (2015) Glob Chang Biol 21: 676-697

doi: 10.22498/pages.24.2.82

Methods and techniques for Quaternary paleoenvironmental reconstruction

N'dji dit Jacques Dembele

Bamako, Mali, 26-30 September 2016

Since 2009, WAQUA (West African Quaternary Research Association) has been promoting Quaternary research in West Africa by organizing meetings for researchers involved in Quaternary science.

One of the main issues raised during these meetings is the absence of contributions from West African researchers to the understanding of paleoenvironmental conditions in the region, because of the lack of trained Quaternary scientists. To help address this issue, WAQUA organized a training session for 60 early-career scientists and students from the West Africa region. Attendees were mainly archaeologists, geographers, historians, and botanists, from Cote d'Ivoire, Benin, Mali, Niger and Nigeria.

The four invited speakers discussed Quaternary palynological methods (Chantal Kabonyi, Democratic Republic of Congo), analysis of palynological data (Monique Tossou, Benin), dendrology (Ntamwira Miranda, Democratic Republic of Congo) and quaternary sediments and geomorphological evidences (N'dji dit Jacques Dembele, Mali).

The workshop focused on seven topics that were addressed during the five days. Day one introduced the stratigraphic framework of the Quaternary and the geomorphological evidences of Quaternary paleoenvironments. These presentations were followed by debates and discussions.

The second day was devoted to Quaternary sediments: the different types, their textures and structures; the methodology to analyze the textures and structures; the different environments of deposits and the methodology of their reconstruction; the provenance of the sediments using heavy-minerals analysis; and the use of Quaternary sediments to infer Quaternary paleoenvironmental change. While the morning was devoted to theory, participants spent the afternoon on a field trip to see Quaternary sediments of the Niger River at Bamako (Fig. 1).

Day three focused on Quaternary palynology. Methods were presented to collect, treat and extract pollen samples; to make pollen slides and analyze them using the microscope; to count and classify pollen using morphology and typology; and to build pollen diagrams. The afternoon was dedicated to practical courses. The participants learnt to extract and identify pollen, and build a pollen diagram. The used samples were from honey, as the preparation of sediment sample necessitates hazardous chemicals such as hydrofluoric acid.

Figure 1: Workshop participant Diarra Cheick Oumar sampling a lacustrine profile of the Niger River right bank, near Bamako, during the field excursion.

The morning of the fourth day was dedicated to archaeology. Presenters discussed the types of archaeological sites in West Africa, the Paleolithic and Neolithic Periods of West Africa, and the archaeological excavation techniques in the West African context. The afternoon was spent discussing major issues concerning paleoenvironmental research in West Africa, such as the lack of quaternary science courses in West African universities; the fact that African researchers have to send their samples to Europe and Asia for analysis; the lack of communication between researchers from different regions; and the lack of funding.

The fifth and last day of the training workshop was used to define new research paths for possible paleoenvironmental research; to discuss publishing issues (language, high fees, and lack of paleo journals interested in West African case study results). The participants proposed to investigate the options for creating a new PAGES working group on paleoenvironmental dynamics of the Niger River during the Holocene. Also, following on from the day's discussions, a group was mandated to assess the feasibility and scope for a new journal where Quaternary scientists from West Africa could publish their results more easily. It was also proposed that WAQUA should hold a workshop every year so that West African researchers can remain informed about new research methods and techniques.

In addition to the various daily agendas, a session titled "Meet the Experts" was held every day during the training workshop, to enabled early-career researchers and doctorate students to discuss their research issues with senior scientists. The participants felt inspired following this much-welcome training meeting and look forward to implementing their new skills and interact with the new colleagues they met.

ACKNOWLEDGEMENTS

WAQUA members want to express their sincere gratitude to PAGES and the University of Social Sciences and Management of Bamako (USSGB) for their financial and material support, and for their encouragements.

AFFILIATION

Faculty of History and Geography, University of Social Sciences and Management of Bamako, Mali

CONTACT

N'dji dit Jacques Dembele: ndjijacques@icloud.com

doi: 10.22498/pages.24.2.83

CLIVAR looks to the future at conference marking 20th anniversary

Jing Li[1] and Nico Caltabiano[2]

Qingdao, China, 18-25 September 2016

More than 600 scientists from 50 countries gathered in Qingdao, China, for the second CLIVAR Open Science Conference (OSC). The event was titled "Charting the course for climate and ocean research" and marked the 20th anniversary of CLIVAR. Over the course of five days, scientists showcased major advances in climate and ocean research. By design, more than one third of participants were early-career scientists, who presented their work through 234 posters and oral presentations, including plenary talks (Fig. 1).

Throughout the conference, the value of cross-disciplinary integration and international cooperation was emphasized. Critical issues addressed included the impacts of a warming ocean on future climate; regional variations in ocean and climate warming; the respective contributions of thermal expansion and melting ice to sea-level rise; the connections between the oceans and the global water and energy cycle; the changes taking place deep in the ocean; and the consequences of excess carbon on sea life. Different aspects concerning climate or proxy modeling that could bring about closer interactions between PAGES and CLIVAR were highlighted during the PAGES Town Hall at the CLIVAR OSC, with specific focus on: regional and high resolution modeling for paleoclimate studies; proxy modeling and assimilation of paleo observations in climate models; study on monsoon and changes in ENSO-monsoon teleconnections at different timescales, etc. Both parties could benefit from common model simulations, data syntheses and methodologies in future cooperation.

Closing a successful week of high-level talks and discussions, and new or strengthened collaborations, the final day of the conference was devoted to climate information for sustainable development and the future of climate and ocean science. Presenters and panelists concluded that CLIVAR of the future needs to help build a society resilient to environmental changes by expanding the understanding of uncertainty in climate risk and providing regional climate information and seamless predictions across timescales. All participants argued for a continued international CLIVAR coordination effort to improve our observational records (including paleo), models and process understanding, and our ability to communicate scientific discoveries translating knowledge into useful information. It was emphasized that further improvements in our understanding of climate processes are required, covering scales ranging from a centimeter to global and from hours to decades, and longer.

Figure 1: Plenary session during the CLIVAR Open Science Conference.

One of the important aims of the conference was to engage the future generation. Jointly with the OSC, CLIVAR successfully organized an Early Career Scientists Symposium (ECSS), hosted by China's First Institute of Oceanography, State Oceanic Administration (FIO/SOA). More than 120 students and early-career scientists (some of them supported by PAGES) participated in the symposium. Participants enjoyed an informal atmosphere, while discussing in groups the key research challenges that the scientific climate community faces at the moment and highlighting the need for international science collaboration. They also discussed the best ways to engage potential stakeholders with their scientific information and suggested their vision for the future of CLIVAR.

The conference injected an amazing degree of enthusiasm about CLIVAR's research and fortified the notion that CLIVAR is and will be critical to meet society's needs for climate information. International cooperation of the type that CLIVAR fosters will continue to be indispensable to developing the human capacity and infrastructure that underpin all major scientific breakthroughs. The conference certainly helped in handing over the enthusiasm for CLIVAR and its science to the next generation, whose excitement is a promise for a very bright future.

The conference was hosted by the Qingdao National Laboratory for Marine Science and Technology - a new campus designed to be an open and innovative world-class marine research center. More details about the Open Science Conference can be found at www.clivar.org.

AFFILIATIONS
[1]International CLIVAR Project Office, Qingdao, China
[2]International CLIVAR Project Office, Southampton, UK

CONTACT
Nico Caltabiano: nico.caltabiano@clivar.org

CONTENTS

ANNOUNCEMENTS

EDITORIAL

SCIENCE HIGHLIGHTS: CLIMATE CHANGE AND CULTURAL EVOLUTION

PROGRAM NEWS

WORKSHOP REPORT

PAST GLOBAL CHANGES

PAGES International Project Office
Falkenplatz 16
CH-3012 Bern
Switzerland

Telephone +41 31 631 56 11
Email pages@pages.unibe.ch
Website www.pastglobalchanges.org
Twitter @PAGES_IPO

Subscribe to PAGES magazine at
www.pastglobalchanges.org/products/pages-magazine

Series Editors
Lucien von Gunten and Marie-France Loutre

Guest Editors
Claudio Latorre and Janet Wilmshurst

Text Editing
Angela Wade

Layout
Lucien von Gunten

Design
sujata design

Parent program
PAGES is a core project of Future Earth.

Supporters
The PAGES International Project Office and its publications are supported by the Swiss and US National Science Foundations.

Printed on recycled paper by
Läderach AG
Bern, Switzerland

Hardcopy circulation 2450

ISSN 2411-605X

DOI 10.22498/pages.24.2