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# PAST GLOBAL CHANGES
MAGAZINE

# ADVANCING PAST SOCIO–ENVIRONMENTAL SYSTEMS SCIENCE

**EDITORS**
Xavier Benito, Giorgia Camperio, Ignacio A. Jara, Estelle Razanatsoa and Iván Hernández-Almeida

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# News

### Goodbye and welcome to SSC and EXCOM members

PAGES would like to extend a warm welcome to the new Scientific Steering Committee (SSC) members: Lukas Jonkers, Shiling Yang and PAGES Early-Career Network (ECN) representative Juliana Nogueira. In addition, we welcome Martin Grosjean as the new Executive Committee (EXCOM) Co-Chair. We would also like to extend our sincere gratitude to the outgoing SSC members: Elena Ivanova, Ed Brook, and ECN representative Tamara Trofimova, as well as the outgoing PAGES Co-Chair, Willy Tinner, for their commitment and dedication to PAGES throughout their terms.

### PAGES IPO staff update

On 1 February, the IPO warmly welcomed Iván Hernández-Almeida as the new Science Officer. Iván is a geoscientist who specializes in the use of microfossils in paleoscience. He will be responsible for implementing and developing paleoscience activities, managing PAGES products, and networking within the international global change community. You can reach Iván via email: ivan.hernandez@unibe.ch

### New working groups

The Marine Arctic Diatoms (MARDI) working group focuses on diatoms as paleoenvironmental indicators, and aims to improve precision and reliability of diatom-based paleoceanographic reconstructions in the Arctic and subarctic. Find out more and join MARDI activities: pastglobalchanges.org/mardi

The Planetary Boundaries working group aims to explore the interface between paleoecology and the planetary boundaries literature, thereby contributing to the definition of safe operating spaces. Find out more about the group: pastglobalchanges.org/planetary-boundaries

### EGU awards and medals 2023

PAGES would like to congratulate Hugues Goosse and Bette L. Otto-Bliesner on receiving awards at the EGU 2023 conference for their important contributions to the Earth, planetary and space sciences. Hugues Goosse, a PAGES SSC member from 2013–2018, received the Hans Oeschger Medal, and Bette L. Otto-Bliesner, a PAGES fellow and Co-Chair from 2006–2011, received the Milutin Milankovic Medal.

### PAGES Early-Career Award

PAGES is pleased to announce the Early-Career Award (ECA) 2023 recipient is Kevin Nota. Kevin has a PhD in molecular paleoecology from Uppsala University. He is currently a postdoc at the Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany. Details: pastglobalchanges.org/science/pages-awardees/early-career-award

### PAGES Early-Career Network (ECN)

In 2022 the ECN announced its intention to expand its regional representation and welcomed 24 new regional representatives covering Africa, North America, South America, the Middle East, Southeast Asia, Oceania and Europe. In addition, five new members have joined the steering committee: Aditit Dave, Fernanda Charqueño Celis, Kamila Faizieva, Sudhir Bhadra, and Szandra Nemeth.

### Deadline for funding support and new working groups

The next deadline to propose a new PAGES working group and/or to apply for financial support for a workshop is 11 September 2023. Details: pastglobalchanges.org/support

### Call for Applications: PAGES-IAI Fellowship Program

PAGES and the Inter-American Institute for Global Change Research (IAI) are pleased to announce the third call for Latin American and Caribbean early-career scientists pursuing research experience in paleoscience within the Latin American and Caribbean area. It will cover the costs associated with travel and living expenses. The deadline for applications is 18 August 2023. Details: pastglobalchanges.org/support/pages-iai-fellowship

### Call for applications: PAGES Inter-Africa Mobility Fellowship Program

The third call for early-career researchers (ECR) interested in building their paleoscience network within Africa is open. This program aims to provide some financial support for travel and living expenses to ECRs who are studying at African institutions and are interested in gaining experience in another African country. The deadline for applications is 18 August 2023. Details: pastglobalchanges.org/support/pages-fellow-africa

### *Past Global Changes Magazine*: Hard copy orders

In an effort to reduce PAGES' carbon footprint and ensure hard copies of magazines arrive at their intended destinations, PAGES now requests that anyone interested in receiving a hard copy update their postal address on the PAGES people database, or complete the online webform. All details and deadlines are communicated in the PAGES newsletter. More information: pastglobalchanges.org/news/137215

### Upcoming issue of *Past Global Changes Magazine*

The next magazine, guest edited by early-career members of the DEEPICE training network and Ice Core Young Scientists (ICYS), focuses on ice-core research. Although preparations are well underway, if you would like to contribute, please contact our Science Officer: ivan.hernandez@unibe.ch

# Calendar

**Past Global Changes (PAGES) Symposium 2023**
1 June 2023 - Bern, Switzerland

**PlioMioVar Workshop: MioOcean Temperature Synthesis Meeting 2**
8 June 2023 - Utrecht, Netherlands

**3rd ACME workshop: Best practices and data quality challenges for coastal marine proxies in the Arctic**
12 July 2023 - Rome, Italy

**Summer School on Speleothem Science (S4)**
7-13 August 2023 -São Paulo, Brazil

**QUIGS workshop - Interglacial intensity**
19-22 September 2023 - Grenoble, France

pastglobalchanges.org/calendar

# Featured publications

### VICS

Guillet S et al. published an article in *Nature* where they reveal how their analysis of medieval texts assisted in the precise dating of some of the largest volcanic eruptions the world has ever seen. pastglobalchanges.org/publications/137198

### Q-MARE

In their paper published in *Proceedings of the Royal Society B*, Agiadi K et al. investigated the effects of Pleistocene climate warming on mesopelagic fish size in the eastern Mediterranean. pastglobalchanges.org/publications/137148

### OC3

Muglia J et al. published a paper in *Scientific Data* which describes the OC3 working group database; a compilation of $\delta^{13}C$ and $\delta^{18}O$ data from benthic foraminifera in deep ocean sediment cores, with particular focus on the last deglaciation (19-15 kyr BP). pastglobalchanges.org/publications/137171

### PALSEA

Rovere A et al.'s paper in *Earth System Science Data* presents the first version of "The World Atlas of Last Interglacial Shorelines (WALIS)". This global database of sea-level proxies samples dates to Marine Isotope Stage 5 and aims to be a valuable resource to the broader paleoclimate community. pastglobalchanges.org/publications/137077

### SISAL

Using a speleothem isotope and growth model, Skiba V and Fohlmeister J published in *Geochimica et Cosmochimica Acta* an investigation of contemporaneously growing speleothems in order to better understand differences in isotopic composition and growth rates. pastglobalchanges.org/publications/137206

# Cover

The study of past socio-environmental systems is interdisciplinary. Images illustrate different archives (rock carvings, stalagmites, archaeological pits and submerged landscapes, petroglyphs) from a variety of geographic regions (India, Australia, Chile, Bolivia). Photo credits: Nivedita Mehrotra, Elena Argiriadis, Antonio Maldonado, Stefani Crabtree, Mayank Mishra, Giorgia Camperio, Christophe Delaere, and Simon Connor.

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# Advancing past socio-environmental systems science

Xavier Benito[1], G. Camperio[2,3], I.A. Jara[4] and E. Razanatsoa[5]

We dedicate this special issue of *Past Global Changes Magazine* to our dear colleague Daniele Colombaroli, who passed away on 11 August 2022. Daniele was a passionate scientist and a compassionate human being with a deep commitment towards innovating paleoscience research through building communities. He was known for his openness, generosity, and ever-readiness in supporting students and colleagues.

Daniele greatly contributed to PAGES' mission in advancing paleoscience research since his PhD days at the University of Bern. He was instrumental in steering PAGES Global Paleofire Working Group (WG) 2 (pastglobalchanges.org/gpwg2), and establishing the Global Paleofire Database (paleofire.org) as the first open-access archive of fire records across the world. Daniele was an avid advocate of bridging science-policy gaps, thus, creating the PAGES DiverseK WG (pastglobalchanges.org/diversek) which merges paleoecology and local knowledge for better decision-making on environmental and social justice issues.

Daniele utilized paleoecological tools to explore past socio-environmental systems (SES), defined as groups of humans, social elements, and processes that interact with each other and the environment through time (Biggs et al. 2021) and he excelled in his work on the legacy of human impact on present landscapes (Colombaroli et al. 2007, 2014). This need for interdisciplinarity that was key to Daniele's work on understanding feedbacks and interactions between past natural and human systems is the highlight of this special issue (Fig. 1). Whereas theoretical and practical implications in studying past SES have been a central topic for PAGES over the last decades (Dearing et al. 2007; Gillson et al. 2017; Latorre et al. 2016), recent perspectives on effective collaboration open new avenues. Crabtree (p. 4) introduces the emerging field of archaeoecology that uses tools and approaches from ecology combined with the archaeological record. Recovering past human perceptions in the face of natural hazards, such as volcanic eruptions, can be achieved by merging paleoecology and art (González p. 6). The application of environmental proxies affected by different spatiotemporal processes (diatoms, ichthyofauna) enables nuanced reconstructions of past human–environmental trajectories in archaeological sites (Zarza et al. p. 8).

The study of past socio-environmental systems also requires developing new methods to disentangle multivariate Quaternary records. Connor (p. 10) reviews recent techniques on landscape reconstruction coupled with the study of ancient DNA in sediments. New approaches in karstic lakes can complement archaeology in understanding the role of the environment in cultural and religious manifestations of the Maya (Rodriguez-Abaunza and Correa-Metrio p. 12). In tropical savannas, determining the role of fire in shaping human–environmental dynamics can be better appraised by analysing pyrogenic compounds from stalagmites (Argiriadis et al. p. 14).

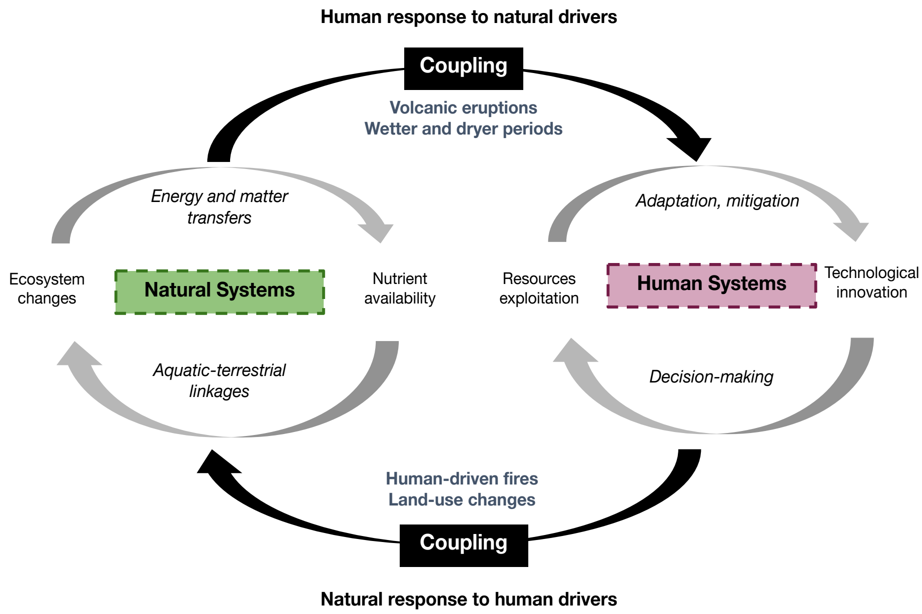


**Figure 1:** Diagram showing between and within-systems coupling (natural and human systems), which is the main topic of the current issue. Black arrows represent human (natural) responses to natural (human) drivers. Contributions are placed in the coupled socio-environmental systems framework, adapted from Zimmerer and Vanek as cited in serc.carleton.edu/integrate/teaching_materials/food_supply/student_materials/1059.

Some studies attest to the importance of regional perspectives for the application of paleoenvironmental and paleoclimatic reconstructions in archaeological sites. Understanding past landscape transformations by Indigenous communities in tropical floodplains is fundamental to present-day management (Lombardo p. 16). Regardless of past precipitation regimes, water availability has shaped cultural innovations to adapt to extreme climatic fluctuations in the central Altiplano (Delaere et al. p. 18), northern Chile (Maldonado et al. p. 20), and western India (Bhattacharya et al. p. 22). Yet, interactions among components of past SES are often asynchronous and nonlinear, with context-dependencies in natural and social processes (Orijemie et al. p. 24). The scaling-up of paleoenvironmental and archaeological records represents an opportunity to hypothesize causes of change across larger spatial and temporal scales, supported by strong locally-rooted inferences, while acknowledging sampling limitations, especially incomplete fossil records. This is particularly the case of environmental drivers in hominin evolution (Kinyanjui et al. p. 26), and cultural responses to global climatic events such as the one at 4.2 ka (Mehrotra and Shah p. 28).

This special issue on past socio-environmental systems speaks to Daniele's dedication for generating, disseminating, and applying new knowledge. It advocates for mobilization and collaboration as a cornerstone for advancing paleoscience research in under-represented regions of the globe (Kulkarni et al. p. 30). Therefore, this collection of articles represents Daniele's view on transcending disciplines, merging diverse evidence, and establishing networks.

AFFILIATIONS
[1]Continental and Marine Waters Programme, Institute of Agrifood Technology and Research, IRTA, La Ràpita, Spain
[2]Department of Earth Science, ETH Zürich, Switzerland
[3]Department of Surface Waters, Research and Management, Eawag, Dübendorf, Switzerland
[4]Departamento de Ciencias Históricas y Geográficas, Universidad de Tarapacá, Arica, Chile
[5]Department of Biological Sciences, University of Cape Town, South Africa

CONTACT
Xavier Benito: xavier.benito.granell@gmail.com

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# Archaeoecology: Using archaeological data to study ecosystems of the human past

Stefani A. Crabtree[1,2,3]

**Archaeoecology is a newly emerging field that uses tools from ecology combined with data from the archaeological record. This new field provides a bridge between paleoecology, which generally focuses on periods before major human impacts, and modern ecology.**

**How can archaeology deepen our understanding of past ecosystems?**
What if archaeology could partner with ecology and paleoecology to give us a better depth of understanding of anthropogenic change? The reconstruction of past ecology allows us to understand changes in the biosphere, to look at long-term ecological fluctuations, paleoclimates, extinctions, speciations, and habitat changes, which are all germane to challenges facing planet Earth today. This is embraced in paleoecological studies which study the ecology of Earth long before *Homo sapiens* spread across the planet (Rull 2010); yet, there is a wealth of data on how societies interacted with ecosystems in the past, encompassing the extinction of Pleistocene megafauna and continuing throughout the Holocene. Archaeology has long examined the ways that humans impact environments, and how environments impact societies in the past, with these studies falling under the umbrella of environmental archaeology. But, these studies have often neglected to incorporate ecological modeling on archaeological timescales, and have primarily focused on the abiotic environment. With improvements in computational technology, advancements in ecological modeling, and the digitization of archaeological records, it is now possible to gain a more comprehensive understanding of entire ecosystems from the archaeological past.

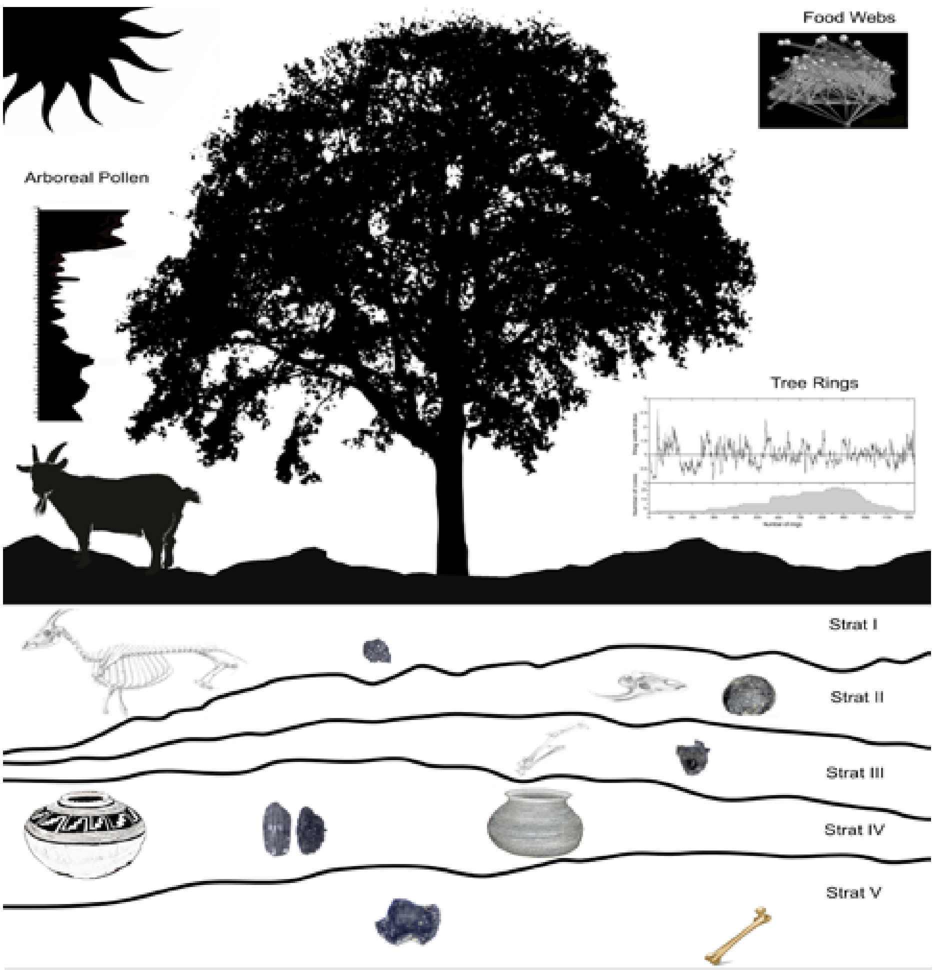


**Figure 1:** Visual description of the ways that archaeology and ecology can bring data together to create a better understanding of the human place in ecosystems. Here we see the archaeological deposition below a modern ecosystem. We can use the archaeological deposits, such as pollen and bones, to understand what the past ecosystem was and how it relates to a modern ecosystem. In this figure we show how classical environmental archaeology (palynology, dendrochronology, pottery analysis, zooarchaeology) can be combined with modern ecological data (e.g. juxtaposing zooarchaeology of caprid to a modern goat) and computer-aided techniques (like food web modeling). Taken together, the modern ecosystem plus the archaeological ecosystem can enable a deeper understanding of ecological trends. Modified from Crabtree and Dunne (2022).

Recently, we proposed the formal definition of the field of archaeoecology (Crabtree and Dunne 2022). Archaeoecology explicitly integrates questions, data, and approaches from archaeology and ecology, highlighting how archaeological data can be a partner for paleoecological and modern ecological studies. This type of research is not new (Revelles 2021). There are instances in the literature going back decades that address aspects of how humans interact with other species and ecosystems in deep time, and there are increasing calls for integration and synthesis that support interdisciplinary research on these types of questions (e.g. Haldon et al. 2018).

**What is archaeoecology?**
What is new in this approach is the coalescence of approaches, topics, and prior and future studies under the name archaeoecology, much as paleoecology emerged at the intersection of paleontology and ecology in the first half of the 20th century. By blending contemporary ecological modeling methodologies with archaeological data, we can enhance our knowledge of the trajectory of human-ecosystem interactions across the past 60 kyr. Archaeoecology, then, can be partnered with modern studies of anthropogenic change. By understanding the ways that people in the past manipulated and changed ecosystems, by examining the full connection of these ecosystems, and by modeling these changes, we can better understand the human place in ecosystems worldwide. Archaeoecology, we believe, will enhance the transfer of knowledge and methods across adjacent disciplines and support novel lines of research. Moreover, archaeoecology will provide new ways to investigate old questions, and can provide pathways for education, development, and collaboration at the intersection of ecology, paleoecology, and archaeology. Most importantly, by defining a field of archaeoecology, we recognize how the study of Homo sapiens in ecosystems in the past can aid us in understanding the human place in ecosystems today, and into the future.

Archaeologists have been studying ecosystems for as long as the field has been formally defined, though often only as one external aspect of past society. For example, Clark defined the field of "ecological archaeology" in the 1930s with the Fenland research project, aiming to understand the surrounding environment of the sites where he worked (Smith 1997). In the 1970s, environmental archaeology was formally

 

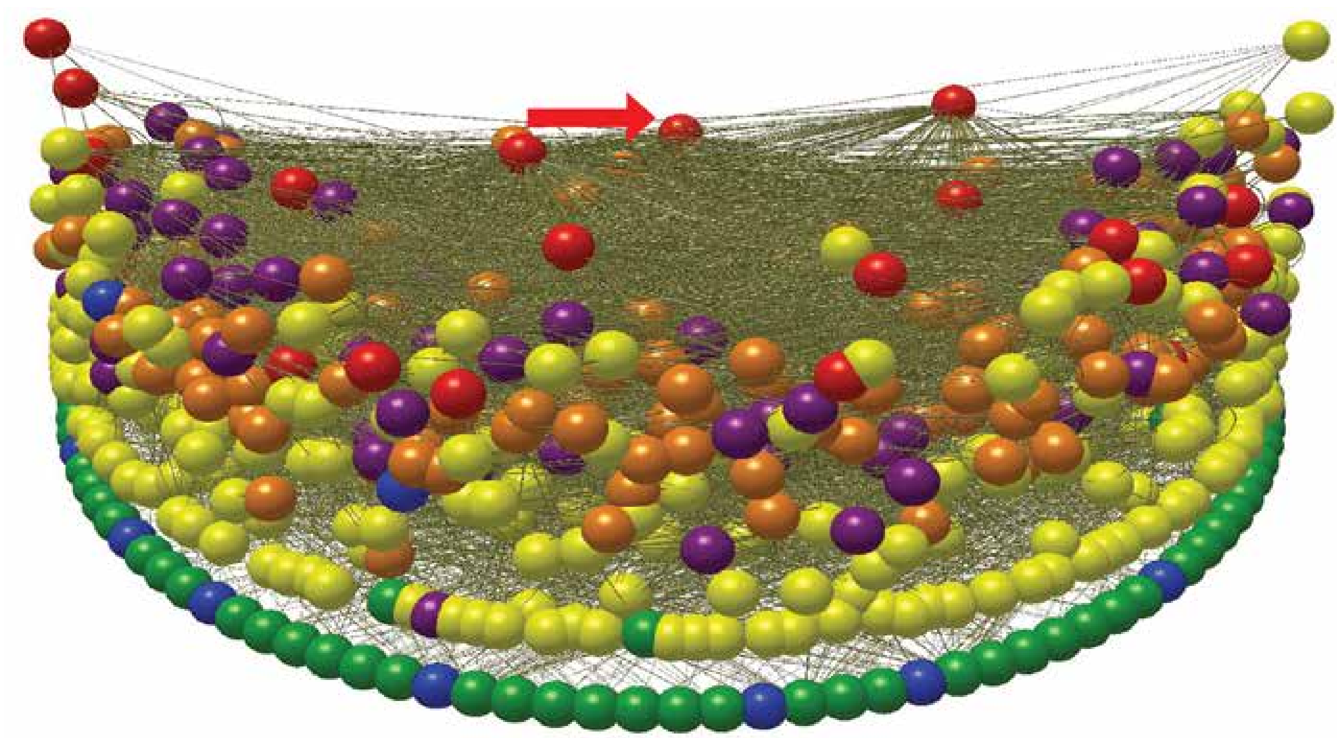

**Figure 2:** Full nearshore food web for the Sanak Aleut people, indicated with the red arrow. Sphere color indicates the type of taxon: green = algae; blue = miscellaneous (e.g. detritus, protozoa, bacteria, biofilm, lichen, seagrass); yellow = invertebrates; orange = fishes; red = mammals; purple = birds. The trophic level of the organism is indicated by how high they are, vertically, in the graph. Lines are feeding links. This was the first archaeoecological study to integrate humans into a full food web and shows the power of combining archaeological and ecological data. Modified from Dunne et al. (2016).

defined as an archaeological subfield leading to more work within the area of studying past environments (O'Connor 2019). Environmental archaeology typically includes studies of the abiotic environmental context reconstructed via geoarchaeological methods, and cataloguing extant plants and animals via zooarchaeology and archaeobotany. The addition of methods reconstructing things such as past temperature (d'Alpoim Guedes and Bocinsky 2018) or rainfall (Bocinsky and Kohler 2014) via computational modeling, have widened the scope of environmental archaeology. A similar widening of the scope of work via ecological modeling approaches has recently emerged by moving beyond presence/absence accounts of zooarchaeological and archaeobotanical remains, to interactions among taxa in the past (Crabtree et al. 2017). These studies do not typically encompass an understanding of full ecosystems of the past, presenting an opportunity.

Archaeoecology, thus, provides the opportunity to move beyond environmental reconstructions of the abiotic context, building past ecosystems via computational models from the data that archaeologists have been curating for decades (Fig. 1). To do this, archaeoecology integrates the increasingly detailed empirical record of archaeological traces, zooarchaeological and archaeobotanical remains, environmental data, and information on extant species and ecosystems, and makes use of methodological advances in areas such as statistical analysis, computational modeling, information theory, and network analysis (Crabtree and Dunne 2022). In this way, this field is novel, as it explicitly uses ecological approaches to model not only the human place in an ecosystem, but the full connectivity of the past ecosystem's components.

### An example of archaeoecology in practice

One example of a published archaeoecological study is the work led by Dunne et al. (2016) examining the Sanak Island food web. For this study, researchers created full food webs for the intertidal and marine systems of the Sanak Islands, linking these food webs with data from archaeological excavations studying the Aleut fisher/hunter/foragers, as can be seen in Figure 2. This study showed the human place in the ecosystem – how humans were highly generalist feeders – and used simulations to show how humans were poised to create cascading impacts on the food web, but did not. This work is one way of showing how the blending of archaeological data with ecological models can lead to greater insights in coupled human-natural systems.

### Archaeology as evidence of past ecological interactions

Using new methodological approaches with already collated data provides avenues for many practitioners going forward with this area of study, and enables new ways to work with archival data. As more archaeological sites are analyzed, digitized, and recorded, archaeoecologists can compare similarities and differences across societies, deepening our understanding of the human relationship with ecosystems through space and time (e.g. Freeman et al. 2018). Furthermore, archaeoecology can serve as a valuable connection between paleoecological and ecological studies, using our knowledge of past events at various timescales and critical moments in Earth's history, to enhance and transform our understanding of existing and future ecosystems.

Archaeological records can serve as evidence of past experiments in sustainability, allowing for a better understanding of modern challenges such as the predicted wave of extinctions and community restructurings likely to be caused by climate change. By examining when and where human actions have positively impacted ecosystems, negatively impacted them, or had no effect, scientists and policy makers can be better equipped to make recommendations for ecosystem resilience in the face of massive change. As a result, archaeoecology can play a crucial role in addressing the challenges of the Anthropocene.

AFFILIATIONS

[1]Department of Environment and Society, College of Natural Resources, Utah State University, USA

[2]The Santa Fe Institute, Santa Fe, USA

[3]Australian Research Council Centre of Excellence for Australian Biodiversity and Heritage, Cairns, Australia

CONTACT

Stefani A. Crabtree: stefani.crabtree@usu.edu

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# Connecting paleoecology and art: A novel approach to recall socio-ecological memories in inhabited volcanic settings

Catalina González-Arango

**Artistic approaches exploring concepts such as disturbance, resilience, and memory might help to connect paleoecology and traditional knowledge in active volcanic socio-ecological systems.**

Inhabited volcanic territories are socio-ecological systems (SES) comprising not only the physical environment (i.e. geological, biological, climatic), but also social agents (e.g. ideologies, governance systems, beliefs). Thus, volcanic SES emerge from the interdependences between nature and culture, and constitute the perfect setting for addressing questions related to resilience and adaptation to natural hazards (Pardo et al. 2021).

**Socio-ecological systems across timescales**

Geologic, ecologic, and human processes occur at different temporal and spatial scales. Therefore, understanding their interactions is crucial for providing a firm underpinning for the interpretation of volcanic SES. For example, volcanoes can exist for millions of years, but eruptions can occur in the order of hours–years. Similarly, ecosystems at volcanic settings might be simultaneously modulated by forces that operate at very different timescales (e.g. orbital forcing or a pyroclastic flow). Human systems are not the exception, and current SES are built by many generations of people who have coexisted with natural phenomena in many different and dynamic ways (Fig. 1).

In this context, the interaction between processes and scales must be considered when reconstructing the long-term history of SES, and connect it with present generations. Therefore, an integration of methodological frameworks, wherein humans are components of processes operating at multiple spatial and temporal scales, is necessary.

Paleoecological multi-proxy techniques are tailored to face such complexity. Reconstructing the history of volcanic ecosystems through time, by simultaneously comparing vegetation (e.g. pollen), geological (e.g. geochemistry), and human-related proxies (e.g. charcoal from human-ignited fires, archaeological remains), offers the unparalleled possibility to reconstruct multiple lines of evidence throughout millennia. Such reconstructions serve as scenarios for testing hypotheses on causality, interconnectedness, and coexistence between natural and anthropogenic factors.

However, connecting the results from paleoecological reconstructions to modern societies is challenging, and they are rarely informative and meaningful enough to intervene in present configurations of SES. Here is where art becomes a powerful tool to fill the gap between past and present settings.

In volcanic settings such as the Doña Juana volcano in southwestern Colombia, the last volcanic eruption occurred almost a century ago (Pardo et al. 2023). However, people inhabiting such territories today struggle with the idea that their home is still an active volcano. The consequences of past eruptions on ecosystems and human societies have been buried and eroded by time. This poses the challenge of learning how past societies coexisted with this type of natural hazard.

Art has the power to evoke meaningful and emotional reactions in people, connecting personal memories to pasts generation. It may also connect with non-material aspects of such relationships (e.g. religious beliefs), which are completely out of the scope of paleoecology. Art, thus, acts as a bridge between our scientific-based findings and modern societies in many ways. Art helps to recall and reconstruct hidden and lost memories, which in this case involve plants, climate, and the volcano as evolving entities. Art might be used as an ethnographic tool to collect and share information about current and past human practices and knowledge, which might become crucial when interpreting paleoecological diagrams.

Here, two specific examples where art compliments paleoecology are presented. They not only help to communicate scientific concepts, but also provide new avenues to co-construct knowledge between local tradition and science. These experiences derive from the ongoing study of inhabited active tropical volcanoes (Pardo et al. 2021; Fig. 2).

The first example is inspired by the effect of fire in volcanic settings, which is preserved and gets manifested as individual burned trees. By using fire in the lab/studio, we can mimic the charring process that occurs naturally during eruptions and learn about wood preservation and the specific environment around the tree. The second example is the use of cyanotypes as an artistic technique that we have used with local communities to explore

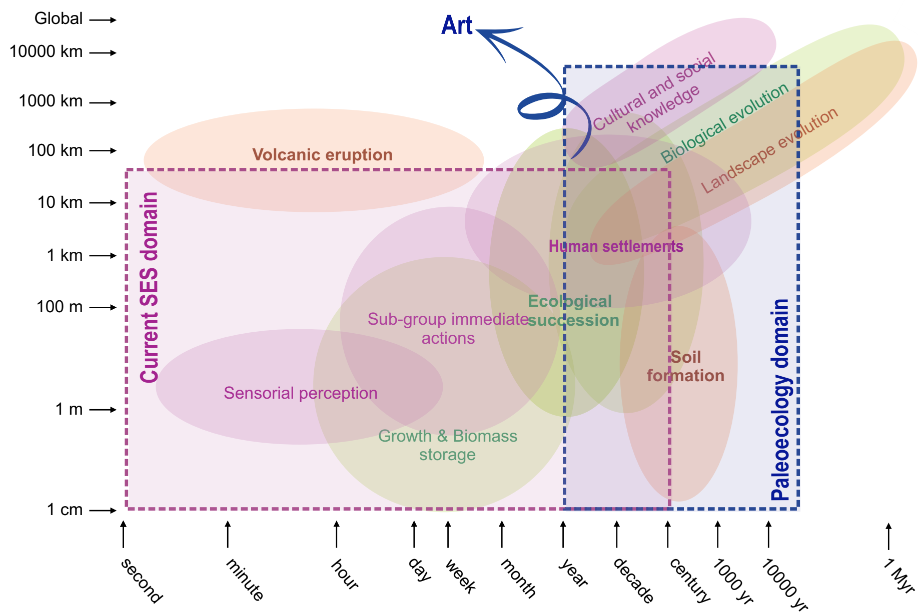


**Figure 1:** Multi-scalar nature of volcanic SES. Ecological (green), geological (orange) and cultural (purple) processes across temporal and spatial scales. Art might serve as a connector between current SES and paleoecological approaches. Modified from Pardo et al. (2021).

 

intergenerational memories about plants inhabiting the ecosystem near the volcano.

**Recalling the memory of single trees through fire**

Reconstructing past fires has become one of the main areas of interest when tackling past human–nature interactions. Fire in paleoecology is traceable by performing charcoal analysis in sediments, and more recently, with the help of more sophisticated techniques, paleoecologists have been able to distinguish between different fire regimes, combustion types, and fuel sources (e.g. Vachula et al. 2021). Ancient human practices related to, for example, cooking, hunting, or certain agricultural systems, can thus be traced back and differentiated from one another. But natural wildfires are also particularly common in volcanic settings, and are responsible for triggering deep and instantaneous changes in SES. In volcanic settings local fires are often caused by lightning, which is common during eruptions, but most of all, due to the high temperatures of pyroclastic and lava flows burning vast extensions of land and human infrastructures in their paths. In some cases, charred remains can be instantly buried by ash or lahars, favoring their exceptional preservation, and turning them into time capsules for next generations.

In volcanic landscapes, particularly where explosive eruptions occurred, it is common to find partially or fully burned timber embedded within large deposits of tephra (e.g. Hudspith et al. 2010). Such botanical remains are exceptionally well preserved and suitable as paleoenvironmental archives due to the water-repellent properties of charcoal, and the rapid burial by ash (Scott and Jones 1991).

Shou Sugi Ban, a Japanese art technique from the 18th century, uses this same principle to weatherproof and preserve wood for decades. In this sense, fire not only works as an agent of destruction, but it is also a medium to preserve legacies. By exploring this dual nature of fire, it is possible to use the remains of charred wood for artistic purposes to communicate ecological and geological concepts related to the history of ancient trees (e.g. age and identity of the tree, discrete vs. continuous processes), which can be difficult to explain to local communities living in volcanic SES. One example of this application is shown in Figure 2b, in which stamp inks are made from charred trunks to communicate about past ecosystems in volcanic SES. These prints are made in such a manner that the same fossil wood serves scientific purposes and artistic exploration.

**Recalling collective memories through cyanotypes**

When trained paleoecologists observe fossil pollen grains under a microscope, it is inevitable for them to make assumptions about past ecological settings in order to come up with an informed reconstruction of specific ecosystems in the past.

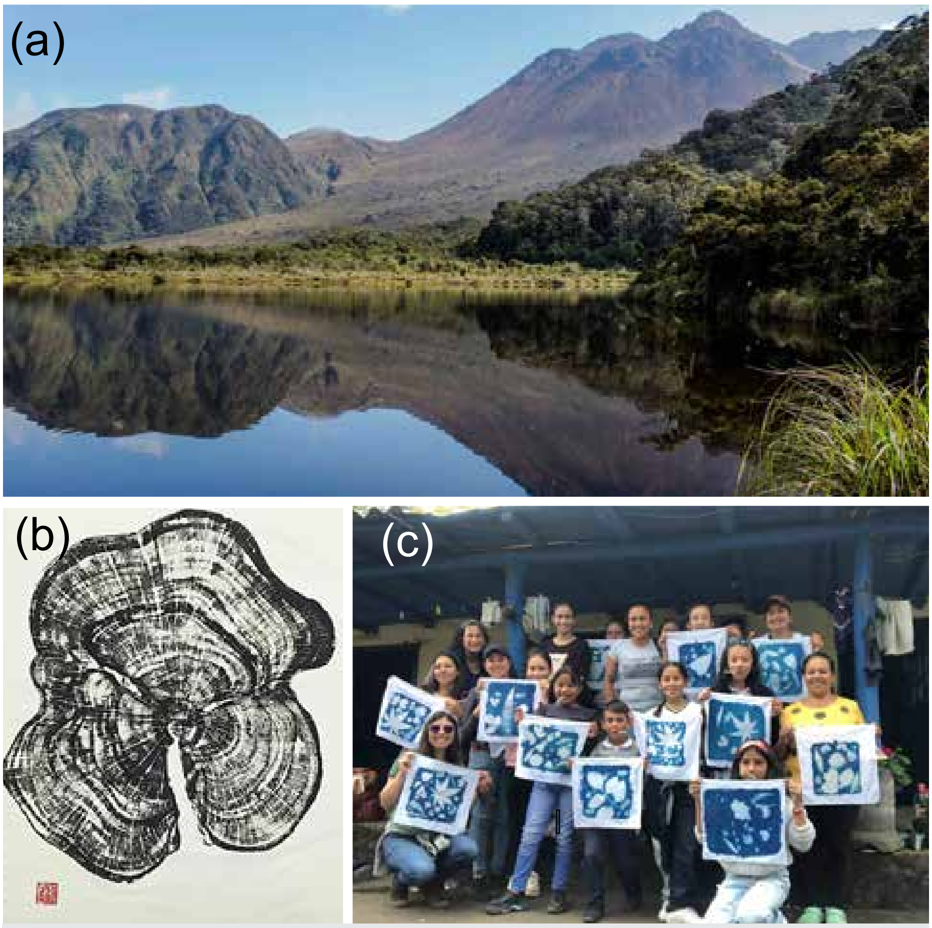


**Figure 2: (A)** Doña Juana volcano in southwestern Colombia (parquesnacionales.gov.co). **(B)** Print of charred wood by C. González-Arango. **(C)** Image of the intergenerational cyanotype workshop with the inhabitants of the volcanic region (Las Mesas, 2022).

But what do those reconstructions mean to the communities which have lived on these sites for generations? Are those paleoenvironmental reconstructions meaningful in a broader context? How can we connect local knowledge to the scientific findings of past ecosystems to better interpret our paleoecological diagrams? Art, once again, might become a powerful tool to connect traditional knowledge of living communities in volcanic SES with scientific paleoecological understanding.

The last eruptive phase of the Doña Juana volcano occurred between 1897–1936 CE, four to six human generations ago. This means that a great deal of the collective memories of the event, and the overall knowledge of the society–volcano interactions, have been partially lost. Despite oral tradition, music, and other cultural expressions about the eruption, the youngest generations are particularly disengaged from the concept of the Doña Juana being a potential natural hazard.

To try to close this intergenerational gap, an art workshop was held in Las Mesas, a small town near the Doña Juana volcano, for children and adult women. They discussed the names, uses, and shapes of plants growing in their territory. We produced cyanotypes using local plants as stencils on fabric, which were then embellished with embroidery. Cyanotype is an ancient photographic technique that uses light and a photosensitive solution to print the shape of objects (e.g. plants), and was extensively used as a technique to document botanical collections in the 19th century.

The workshop allowed all the participants to recall the diverse relationships that people have with plants in their region. Using ancient scientific techniques with an artistic perspective enriched the experience. It facilitated an authentic integration of the participants, closed gaps between scientific and non-scientific knowledge and emotional and rational thinking, and created the encounter between past and present.

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AFFILIATION

Departamento de Ciencias Biológicas, Universidad de los Andes, Bogotá D.C., Colombia

CONTACT

C. González-Arango: c.gonzalez2579@uniandes.edu.co

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# Integration of proxies in human-environmental systems: Paleoecology, paleoclimatology, and archaeology

Macarena M. Zarza[1], X. Benito[2], C. Flores[3,4,5], S.K. Mandal[6], A. Maldonado[3] and S.Y. Maezumi[7]

**Co-developing paleoscience research questions is associated with effective collaboration challenges. We discuss a framework that brings together past socio-environmental processes and proxies to foster future interdisciplinary collaborations.**

## Quaternary records of environmental change

The multivariate nature of environmental changes recorded in Quaternary records informs and enhances our knowledge of past interrelated human and climatic systems. This knowledge is usually inferred from natural archives of paleoenvironmental change (e.g. lake sediments, peat, speleothems, tree rings) which contain evidence in the form of biological, chemical, and physical remains or proxies. Proxies can reconstruct different biotic or abiotic variables (e.g. temperature, precipitation, etc.), which may also be controlled by anthropogenic (e.g. agriculture, land use, deforestation) and non-anthropogenic (e.g. climatic variability, volcanic eruptions, etc.) drivers. The distinction between natural and anthropogenic drivers can be partially disentangled by analyzing paleo proxies, along with archaeological evidence, which provides insights into how, when, and where humans occupied, utilized, and influenced their environment. Yet their interpretation is complex due to their intricate multivariate nature, which often leads to conclusions drawn by simplistic approaches, generating intense debates in the science community (Rull 2018).

Some Quaternary studies have claimed that past environmental events, inferred from proxy data, drive identifiable changes in the archaeological and historical records; so-called correlation means causation. While environmental determinism – societal trajectories being predisposed by physical environment change – is defended by some paleoclimatologists, the criticism comes mostly from the social side of paleoscience (archaeologists, historians) (Coombes and Barber 2005). This type of simplistic determinism survives because of the difficulty of co-developing research questions from different disciplinary backgrounds that are rooted in disparate theoretical perspectives (e.g. humanistic and scientific), methodologies (e.g. theory-driven and data-driven), and multiscale processes (long-short temporal scales) (Silva et al. 2022). The most important challenge in synthesizing paleoecological, paleoclimatological, and archaeological research is to interpret multiple types of data while integrating them in a comparable framework that considers their different temporal and spatial coverage.

In this article, we present a framework to help researchers integrate proxies at the nexus of coupled human-environmental systems (Fig. 1). By adapting the seminal spatiotemporal ecology hierarchy of Delcourt and Delcourt (1983), we present two study cases focused on processes operating at different temporal and spatial scales that examine paleoenvironmental and archaeozoological data, highlighting the links across disciplines. We conclude by generating questions at the interface of paleolimnology and zooarchaeology that consider the scale-dependency of associated biotic proxies, such as when and how humans exploited aquatic resources, and how early humans coped with river floods.

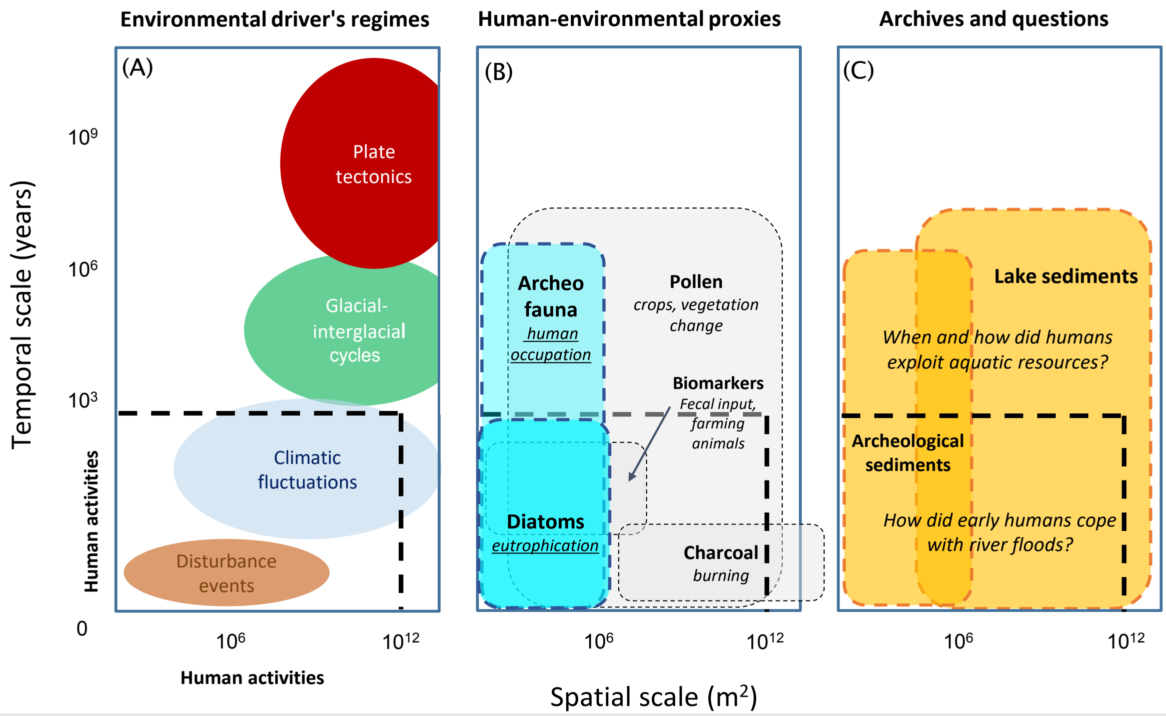


**Figure 1:** Framework to integrate proxies at the nexus of coupled human-environmental systems. Integration of **(A)** environmental driver's regimes, **(B)** human-environmental proxies to address them, and **(C)** archives and questions used in the text. The spatiotemporal scale for each environmental regime, including the scale of human disturbance (dashed black rectangles), and the archives and proxies discussed in the text, reflect the resolution required to study it. Adapted from Delcourt and Delcourt (1983). Note: $10^6$ $m^2$ is equivalent to local scale (e.g. the size of a lake), and $10^{12}$ $m^2$ is equivalent to a regional scale (e.g. the size of a continent).


**Figure 2:** Geographical location of the two study cases presented in the main text. The yellow triangle indicates Lake Llaviucu. The red dot indicates the distribution area of the archaeological sites of the Argentina Gran Chaco.

### Diatoms, paleoecology, and archaeology in the high Andes

Diatoms – unicellular siliceous algae – have been widely used in aquatic ecosystems to infer past changes in climate, land use, and/or water quality that are relevant to archaeological investigations (Smol and Stoermer 2010). A possible application of diatoms in archaeological research is to study aquatic-terrestrial relationships under the influence of humans. Diatoms react sensitively to changes in water nutrients, which are often a direct function of the surrounding landscape via biochemical fluxes of detrital sediments and organic matter. Human practices, by means of terracing, can modify those aquatic-terrestrial relationships. Lake Llaviucu (Fig. 2) is located in the tropical Andes, where an important trade route connecting the highlands of Ecuador with the Amazon lowlands was operated by pre-Inca (3700–471 yr BP) and Inca societies (480–420 yr BP). Using lacustrine sediment cores, Benito et al. (2022) reconstructed the limnological and vegetation histories to infer environmental processes over the last 3 kyr. This multi-proxy study used diatoms, pollen, agropastoralism indicators (charcoal, crop pollen types, Sporormiella spores), and Ti concentrations derived from X-ray fluorescence (XRF) scanning data (a proxy for soil erosion). This suite of indicators was used to record processes at a hierarchy of spatial and temporal scales including: Andean climate, catchment-wide processes, lake-catchment location influencing dispersal of diatoms, or in-lake habitats (benthic and planktic productivity processes).

### Archaeofauna as a paleoproxy in the Argentinian Gran Chaco

Recently, the use of novel zooarchaeological analysis has begun to shed light on the pre-Hispanic human occupation of the Gran Chaco region in Argentina, and its paleoenvironmental evolution, which historically had been inferred using evidence from other areas. The sites of the Argentinian Gran Chaco (Fig. 2) have sequences of human occupation throughout the late Holocene, from 1800 to 600 yr BP (Lamenza et al. 2019). The site "El Cachapé Potrero IV B", studied by Zarza et al. (2019), shows evidence of more than one diachronic human occupation. The temporal frequencies of the archaeofauna record indicate a reduction in the consumption of deer and an increase in fish consumption between 1700 yr BP and 900 yr BP. This, added to other lines of evidence (distribution of sites and ceramic variability) suggest a reduction in areas of resource procurement since 1000 yr BP.

Morphometric analysis of fish remains (Zarza et al. 2022) shows an increasing trend in size over time. This variation can be interpreted as a gradual improvement in favorable environmental conditions for fish communities, such as small variations in lake levels, high dissolved oxygen, food availability, larger size of water bodies and/or smaller fish populations. Zarza et al. (2023) also demonstrated that variability in fish pectoral spines from the species *Hoplosternum littorale* can be used as an indicator of seasonal resource exploitation by humans. Rainy seasons favor the development of a particular morphotype of pectoral spine of *H. littorale* (Hostache and Mol 1998). Thus, its presence in the archaeological record could indicate that the Chaco people were hunting fish during the rainy season (between October and April). These results highlight the importance of ichtio-archaeological studies to infer both past environmental conditions and the use of aquatic resources (Santini 2009; Zarza et al. 2019).

### The importance of scale when integrating paleoecology and archaeological proxies

Humans, climate, and the environment are inextricably linked. The case studies presented here emphasize various spatial and temporal scales recorded by different proxies (diatoms and archaeofauna; Fig. 1b), and archives (lake sediments and archaeological sedimentary matrix; Fig. 1c) (Holdaway and Wandsnider 2008). For example, high-elevation lakes in the tropical Andes are naturally fishless. Under this context, a study of fish skeletal remains from nearby archaeological deposits may indicate resource transportation and human movements. Changes in diatom assemblages from archaeofaunal deposits may also help to identify the provenance of fish (e.g. active dispersers) and their local habitat (riverine or lacustrine), providing new insights into aquatic resource strategies. For the case of Lake Llaviucu as explained above, its land-use history needs to be compared with independent proxies of human occupation (e.g. fecal biomarkers and charcoal) to evaluate the hypothesis of terracing and aquatic fauna exploitation in the valley, considering that these processes act at different spatiotemporal scales (Fig. 1b).

Human settlements in the Chaco are located in dynamic riverine regions. Thus, lacustrine sediment cores have the potential to improve our understanding of the intrinsic relationship between aquatic and terrestrial environments, and past human societies. The potential contribution of diatom analyses to this case study can provide nuanced climatic and environmental contexts under which Chaco's Late Holocene societies lived and adapted. The presence of riverine diatom taxa, for example, would indicate wet conditions, which if compared with regional archaeological excavations and nearby pollen records, would provide information on human practices in the event of major river floods. Increasing the number of radiocarbon dates from the Chaco region and adding higher-resolution paleoclimatic proxies (e.g. sub-decadal) may also help to further elucidate relationships between the use of aquatic resources and human–environment dynamics.

As a conclusion, we highlight the need to complement any multi-proxy study with a comprehensive understanding of the possible processes that shape past socio-environmental systems within the scale of available evidence. Beyond these, data synthesis efforts are a necessary step to develop interdisciplinary research questions and generate comparative data on human-environment interactions (Fig. 1c).

AFFILIATIONS

[1]Anthropology Division, Museum of Natural Sciences of La Plata, Argentina
[2]Marine and Continental Waters Programme, Institute of Agrifood Technology and Research, IRTA, La Ràpita, Spain
[3]Center of Advanced Studies in Arid Zones (CEAZA), La Serena, Chile
[4]School of Archaeology, Universidad Austral de Chile, Puerto Montt, Chile
[5]ANID – Millennium Science Initiative Program-UPWELL NCN19_153
[6]Department of Architecture and Planning, National Institute of Technology, Patna, India
[7]Department of Archaeology, Max Planck Institute of Geoanthropology, Jena, Germany

CONTACT

Macarena M. Zarza: macarena_zarza@hotmail.com

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# Situating past societies in their environments: Emerging techniques

Simon E. Connor

**Past societies have much to teach us about ways of dealing with environmental change. New techniques in landscape reconstruction and ancient DNA are shining a light into the past and revealing how people and environments shaped each other.**

Real understanding of past societies can only come with a holistic view of their place in the world. Today's societies rely so heavily on technology and human-modified environments that we sometimes imagine we act separately from the ecosystems that support us. We need only to look at the economic and health impacts of recent extreme weather, fires, and floods to see how wrong this view can be. The environment shapes how we understand ourselves as humans. In fact, it is humanity's lived experience of past environments that has led to today's environmental knowledge.

### Why situate past societies in their environments?

The link between past experience and present knowledge is what makes the study of past societies and environments so important. Although each day brings new situations, we can all benefit from the experience handed down to us, regardless of whether it was from yesterday or thousands of years ago. Today's technology-saturated societies might imagine that the further we go back into the past, the more direct the relationship between people and their environment. But delving into that relationship is not a straightforward task and becomes more difficult the deeper in time we go. The scientific evidence is often indirect, fragmented and murky.

Archaeologists study this fragmented evidence to understand past societies, and paleoecologists delve into mud to understand past ecosystems. By talking to each other, we can work towards a shared understanding. Bringing these two fields together presents a number of challenges, however. Reconciling issues of different spatial scale, different timescales and different scholarly mindsets can frustrate attempts to investigate past socio-environmental systems.

### Insights from land-cover modeling

New techniques promise to relieve some of these frustrations. One particularly promising field is land-cover modeling, which turns pollen sequences into realistic estimates of vegetation cover and composition. Land-cover modeling can reveal the extent of past modification of ecosystems by humans, rewriting the history of human activity on the Earth's surface. This can be achieved on various scales, from continental to local, depending on the human-environment interactions of interest. Researchers interested in the major turning points in human history, such as migrations and the emergence of agriculture, might require information about past vegetation on a continental scale. An example of this is a land-cover reconstruction from Europe, which tracks the shifting distribution of Holocene forests, and the rapid expansion of agricultural land across the continent (Githumbi et al. 2022). Reconstructions on this scale provide data that can be compared to archaeological evidence and climatic shifts reconstructed from various paleo-proxy data.

On a regional scale, land-cover modeling can show how ancient cultural practices, like deliberate burning, modified the vegetation. In Australia, for instance, there are few suitable trees for fire-scar studies, meaning there is little information about past fire regimes. Using land-cover modeling, researchers were able to reconstruct past vegetation, showing that Indigenous people created forest environments that were grassier than they are today (Mariani et al. 2022). This information can be useful in managing Australia's wildfire problem. In Czechia, land-cover modeling showed how generations of scientists have made the mistake of thinking spruce forests are recent introductions, rather than the ancient forest ecosystems new evidence shows them to be (Abraham et al. 2016). How we manage these forests depends very much on what we know about their history.

At the local scale, researchers can use land-cover modeling to distinguish between local human activities around archaeological sites, and environmental change occurring across

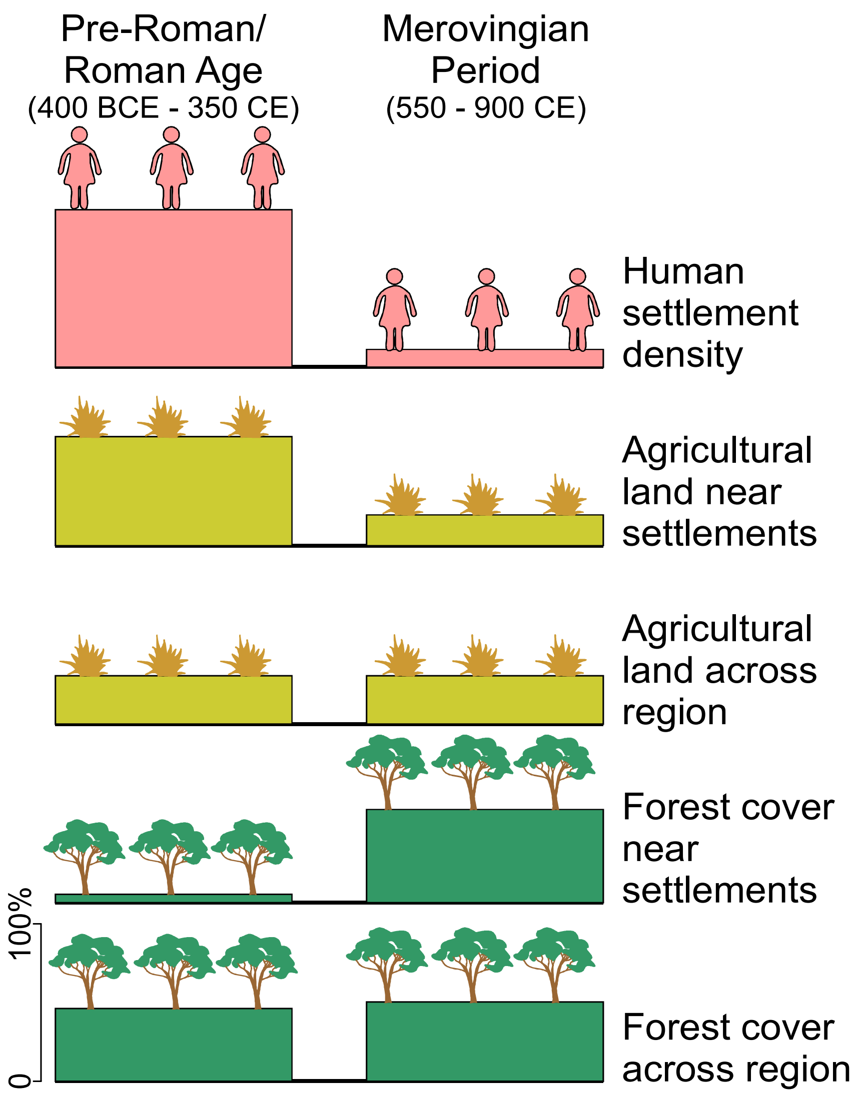


**Figure 1:** Changes in human settlement, agricultural land and forest cover in Central Norway, showing how land-cover modeling can be used to reconstruct past vegetation at local and regional scales. Modified from Hjelle et al. (2022).

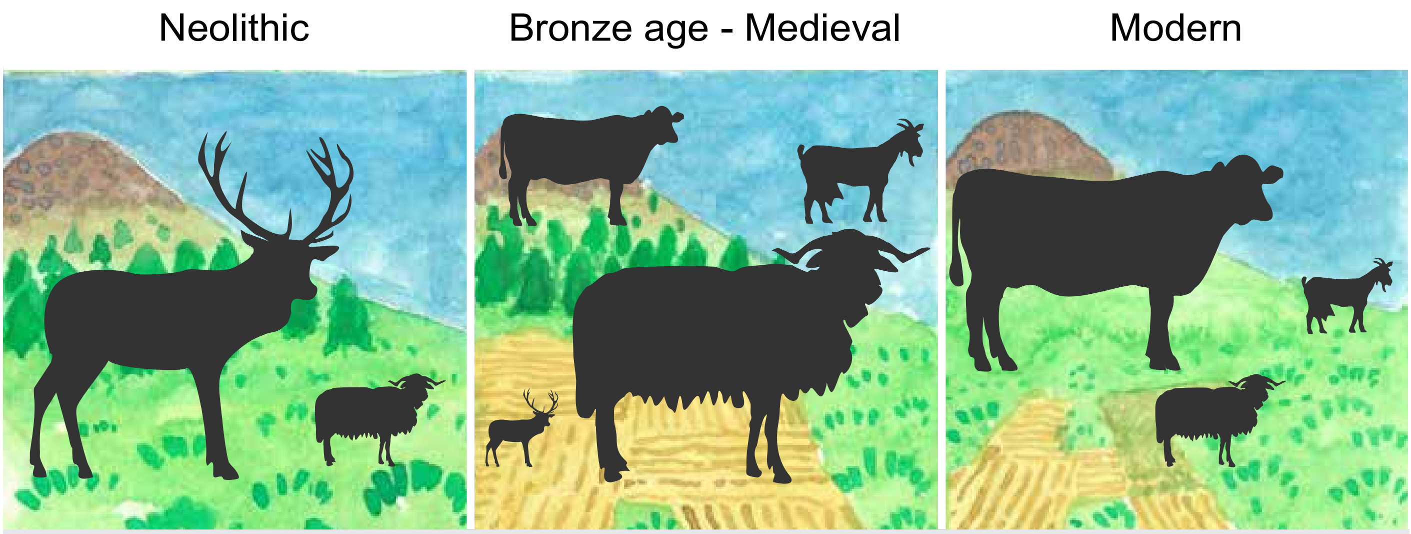


**Figure 2:** Grazing animals at different periods in the Swiss Alps, from the ancient DNA of red deer, sheep, cows and goats found in lake sediments. The size of each animal symbol represents its contribution to overall DNA, and the background symbolizes vegetation changes. Modified from Garcés-Pastor et al. (2022).

the broader region. In Norway, researchers found that trees covered only 5–10% of the landscape near settlements during periods when the area was densely populated, compared to around 50% tree cover across the landscape as a whole (Hjelle et al. 2022). Tree cover expanded after settlements were abandoned (Fig. 1). This level of detail allows us to begin to imagine how our ancestors interacted with their surroundings, adopting different attitudes and practices in near and distant zones.

### Ancient DNA

Ancient DNA is another approach with enormous potential for situating past societies in their environment. Despite its ability to uncover past biological diversity in unprecedented detail, ancient sedimentary DNA (*sed*aDNA) is subject to biases (e.g. preservation) that can make its interpretation difficult (Edwards 2020). For this reason, it is preferable to use *sed*aDNA alongside other proxies, including traditional indicators like pollen, but, also emerging proxies like lipid biomarkers, as unequivocal human traces.

An example is a study of a medieval archaeological site in Ireland, where researchers were able to use *sed*aDNA, novel biomarkers, and other proxies in lake sediments to investigate how people used plants and animals in the past (Brown et al. 2021). Unexpected details of animal husbandry and butchering were revealed from multiple lines of evidence, as well as clear signs of deforestation and the cultivation of plants that are rarely, or imprecisely, identified from fossil pollen. Importantly, their approach had no impact on the archaeological site itself, and, unlike an excavation, it tells us what happened at the site prior to site formation and after site abandonment. In this way, we can begin to understand why people established a settlement, and why they eventually left.

Another example of the use of *sed*aDNA comes from the Swiss Alps, where researchers discovered that pastoral activity had been a key driver of alpine plant diversity for thousands of years (Garcés-Pastor et al. 2022). Unlike some pollen grains that can spread long distances in the air, *sed*aDNA most likely comes from the catchment area, and it provides additional information on animal occupation. This makes *sed*aDNA a very useful indicator of local change in vegetation. The researchers found evidence for changing pastoral practices against a background of vegetation change. People shifted from a reliance on wild fauna to domesticated sheep, goats and cattle through a succession of archaeological periods (Fig. 2). This kind of research shows how different societies in the past were able to balance agriculture, pastoralism, forest resources, and habitat diversity to create unique subsistence patterns in space and time, allowing them to adapt to a dynamic environment.

Suitable archaeological contexts can also yield ancient DNA. In an example from Greenland, researchers used DNA analysis of small bone fragments to find out what Inuit and Norse populations were eating (Seersholm et al. 2022). This research revealed a rich diversity of prey, including many species from the land and sea that are rarely, if ever, preserved or found in archaeological sites. This gives researchers new tools for understanding how people interacted with other species, hinting at the human intelligence that must have been needed to understand, capture and prepare so many different species from their environment.

The examples above come from relatively cool, wet environments, but *sed*aDNA also has potential in semiarid environments with much longer histories of human occupation, such as the African savanna (Tabares et al. 2020). Along with other new proxies, ancient DNA seems to set the stage for a renewal in how we conceptualize the past.

### Better research

Like any new tool, there are important limitations and ethical issues that come into play, especially when dealing with the cultural and genetic heritage of Indigenous peoples. Scientists can often be blind to the deep and intangible cultural associations that belong to certain places and things. There are various frameworks that can guide a more considerate approach to research (de Freitas et al. 2022). It could involve taking a different perspective – seeing landscapes and sites as biocultural heritage (Ekblom et al. 2019) and acknowledging that all environments, despite their apparent "wilderness", are places humans have modified to varying degrees (Fletcher et al. 2021). Or it could involve taking a truly collaborative and ethical approach – one that requires researchers to adopt research practices developed with, and by, Indigenous communities, or to co-design research directly with the communities themselves (AIATSIS 2020; Copes-Gerbitz et al. 2022; de Freitas et al. 2022).

As researchers, we need to remain mindful of the people who created and maintained complex socio-environmental systems over millennia. While new technology and techniques hold much promise, a truly holistic view requires us to consider multiple sources of evidence, and to learn from the descendants of the societies and environments we are trying to study.

AFFILIATION

School of Culture, History and Language, Australian National University, Canberra, Australia

CONTACT

Simon Connor: simon.connor@anu.edu.au

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# Environmental history of the northern Maya Lowlands: Evidence from a karstic lake

Alejandra Rodriguez-Abaunza[1,2] and Alex Correa-Metrio[3]

**Landscape transformation by Maya civilization represents one of the most significant anthropogenic environmental changes in the pre-colonial Americas. Using lake sediments, we address how the evolution of a karstic lake has been affected by human–environment interactions over the last 8300 years.**

The Maya civilization developed and thrived in the region of the Yucatan Peninsula (México, Guatemala, and Belize) from ~4000–500 yr BP (before present). The Puuc region, located at the northwest of the peninsula, was a key area for human settlements, as it harbors some of the most productive soils in the Maya lowlands (Fig. 1). In this region, Maya settled from ~2800 yr BP, and some city-states persisted until the early 11th century (Dunning et al. 2013; Hoggarth et al. 2016). Although today it represents the driest zone of the peninsula, the Puuc region was one of the most densely populated areas during Maya times. These human settlements probably exerted substantial impacts on perennial water sources given the regional vulnerability to water stress. Sediments in karstic aquatic ecosystems widespread across the Yucatan Peninsula (lakes and sinkholes) represent natural archives to investigate human-environment interactions by using different proxies. Lake Yalahau is the largest lake in the northern Yucatan Peninsula and is located relatively close to three major Maya cities from the Puuc region (Fig. 1). There are also archaeological remains of a civic ceremonial center at the northwest of the lake. Thus, the multi-proxy record of Lake Yalahau provides an excellent opportunity to understand the effect of natural stressors and human activities on the lake system over the last 8300 years in the Puuc region.

We recovered a 560-cm-long sedimentary sequence from the deepest part of Lake Yalahau using a modified Livingstone piston corer. Here, we used elemental concentrations and geochemical analysis of organic matter to explore mechanisms of underlying changes in lake evolution. A principal component analysis (PCA) was applied to elemental and geochemical proxy data to summarize environmental variability through time in Yalahau. This technique summarizes the geochemical signals in principal components (PC) that are interpreted as representing climatic and/or environmental drivers, and can be used to infer the environmental evolution of the lake throughout the different cultural stages of the Maya civilization. Major geochemical trends of Lake Yalahau were described in terms of changes in erosion in the catchment (PC1) and lake productivity (PC2) (Fig. 2). Detrital elements (iron and rubidium) were located along negative PC1 values, while authigenic elements (calcium and strontium) were located along positive PC1 values. Negative PC1 scores are associated with an increase in the input of detrital elements to the lake caused by high erosion in the catchment area. Negative correlation of calcium carbonate with total organic carbon in Lake Yalahau suggests that $CaCO_3$ concentrations are influenced by lake productivity. As $CO_2$ increases, as a product of oxidation of organic matter, it lowers pH in the hypolimnion and promotes calcite dissolution in sediments (Dean 1999). Elements associated with poorly oxygenated conditions (sulphur) and high lake primary productivity (total organic matter) were characterized by negative values in PC2, while calcium carbonate concentrations were associated with positive PC2 scores. Thus, negative PC2 scores were interpreted as an increase in primary productivity in Lake Yalahau. Our findings point to anthropogenic activities and regional climatic variability as the main triggers of the lake evolution trends over the last 8300 years.

**Maya Archaic (8300–4000 yr BP)**
The infilling of Lake Yalahau and other lakes in the northern Yucatan Peninsula started at around 8000 yr BP. This process was probably related to regional sea-level rise and a higher moisture availability during the early Holocene in the Northern Hemisphere (Haug et al. 2001; Milliken et al. 2008). PC2 positive scores suggest low productivity conditions in Lake Yalahau (Fig. 2). Humid conditions prevailed at the end of the early Holocene, enabling the establishment of deciduous forests in the northwest of the Yucatan Peninsula (Leyden 2002). This vegetation cover probably protected the soil from erosive agents, explaining the low erosion rates observed in Yalahau from 7000–4000 yr BP through soil stabilization (Koinig et al. 2003). Archaeological remains indicate the presence of hunter-gatherers in the Maya Lowlands during the Archaic period (Hoggarth et al. 2016). However, pollen records show relatively pristine vegetation during this period, implying anthropogenic effects on the environment would have been minimal or limited in their spatial extent (Leyden 2002).

**Maya Preclassic (4000–1700 yr BP)**
Evidence of the first permanent settlements in the Puuc region dates to the Middle Preclassic (Hoggarth et al. 2016). In Lake Yalahau, decreasing PC1 scores indicate increasing erosion probably associated with land-use changes (Fig. 2). The input of allochthonous nutrients, in turn, resulted in increased lake productivity reflected in

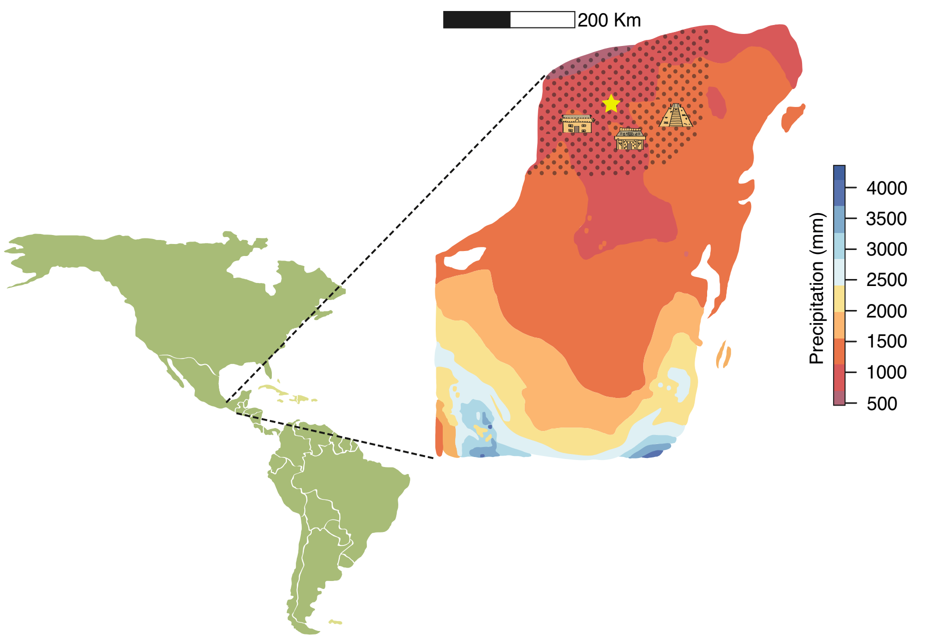


**Figure 1:** Location of the Yucatan Peninsula showing the modern mean annual rainfall distribution (Fick and Hijmans 2017). The Puuc region (marked dotted area) and Lake Yalahau (yellow star). Buildings symbolize main archaeological sites from the Puuc region, from left to right: Oxkintok, Uxmal, and Chichén Itzá (Illustrations by Ariadna Valenzuela-Zuñiga).

 

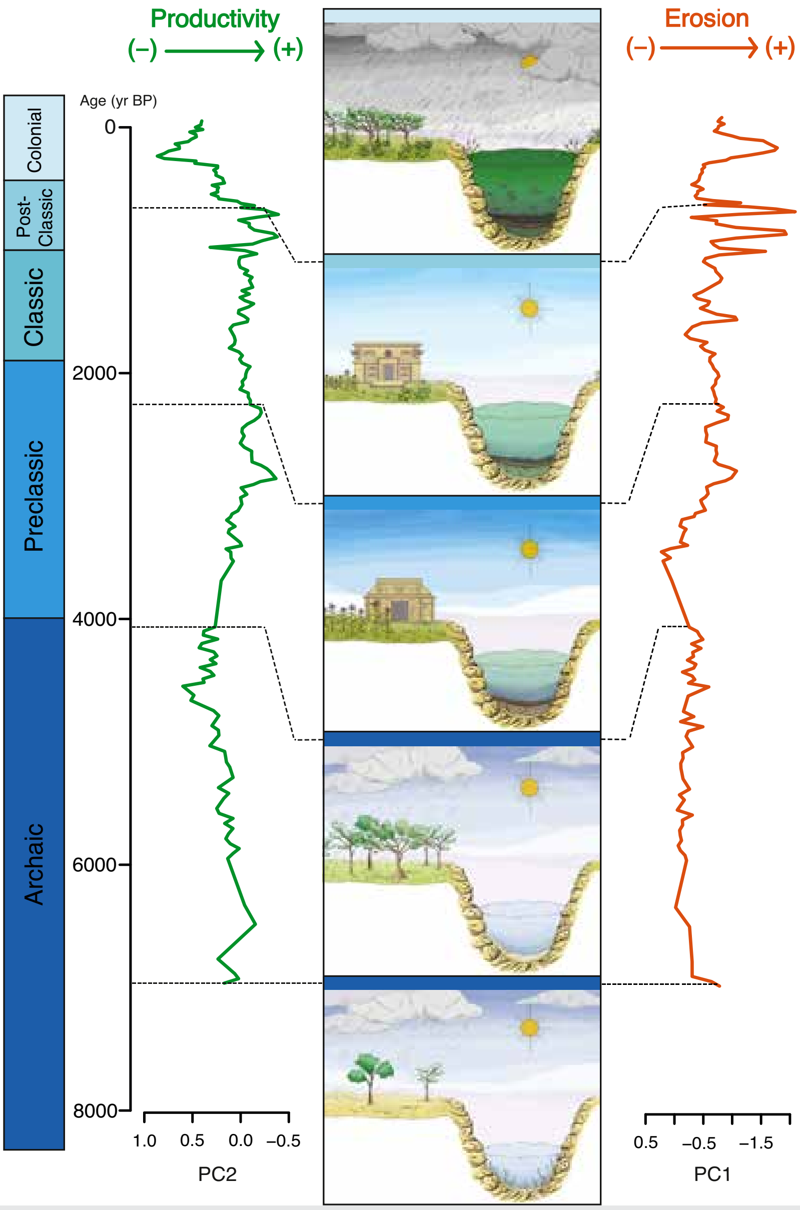


**Figure 2:** Paleoenvironmental synthesis of Lake Yalahau over the last 8300 years based on changes in productivity (PC2 scores) and erosion (PC1 scores). The Maya chronology is shown on the left side (Illustrations by Ariadna Valenzuela-Zuñiga).

changes in PC2 scores. The evidence suggests that deforestation and agriculture were extensive practices throughout the Yucatan Peninsula during the Preclassic (Anselmetti et al. 2007; Leyden 2002; Wahl et al. 2006). Also, lake sediments recorded several pronounced regional droughts (Hodell et al. 2001) that coincide with changes in vegetation cover in Yalahau during the middle to late Preclassic.

**Maya Classic (1700-1000 yr BP)**
During the Classic period, increased erosion in the basin and eutrophication of Lake Yalahau are indicated by both negative PC1 and PC2 scores. These findings coincide with the development of "classic" Puuc architecture in city-states near the lake (i.e. Uxmal), corresponding to a large-scale human occupation of the region (Dunning et al. 2013). Regional paleoclimate records from speleothems and lake sediments show successive droughts during the Terminal Classic that coincide with societal collapse of some city-states in the southern Maya Lowlands (Hodell et al. 2001; Medina-Elizalde et al. 2010). However, archaeological evidence shows an apogee of Puuc sites during the Terminal Classic period. Puuc settlements developed urban reservoirs (aguadas) and underground cisterns (chultunob) for water storage. These water management strategies may have allowed the Puuc populations to deal with droughts better than in other areas of the Maya Lowlands (Dunning et al. 2013; Hoggarth et al. 2016).

**Maya Postclassic (1000-400 yr BP)**
Regional paleoclimate records indicate a severe drought during the early Postclassic that coincides with the decline of construction of monuments and hieroglyphic inscriptions at the Puuc urban centers (Dunning et al. 2013; Hodell et al. 2001; Medina-Elizalde et al. 2010). Hoggarth et al. (2016) suggest a shift in occupation to sites along the coast and nearby freshwater ecosystems such as lakes and rivers during the Postclassic period. The access to perennial water resources, such as those provided by Lake Yalahau, could favor settlements around the lake. During this interval, productivity and erosion rates increased, reaching their maximum throughout the Yalahau record. Also, an increase in tropical hurricanes in this interval would explain enhanced soil erosion and allochthonous sediment input into the lake (Schmitt et al. 2020).

**Colonial (400 yr BP-Present)**
Our record indicates that the last 400 years have been characterized by high erosion rates and a substantial decrease in productivity in Lake Yalahau. These patterns have been associated with increased regional moisture availability and high cyclonic activity (Medina-Elizalde et al. 2010; Schmitt et al. 2020). Environmental degradation associated with human activities coupled with droughts and hurricane effects could explain a decline in the population throughout the Puuc region at the end of the Postclassic period and during Colonial times (Dunning et al. 2013; Schmitt et al. 2020).

Our study illustrates the importance of studying the evolution of these karstic lakes to understand long-term environmental changes in the Maya Lowlands. The sedimentary record of Lake Yalahau shows that anthropogenic environmental degradation may have been one of the main drivers of ecological change since the Preclassic period in the Puuc region. Further archaeological and paleolimnological studies, focused on the human-impact proxies (i.e. pollen and charcoal) and responses of karstic lakes to anthropogenic degradation, will contribute to a better understanding of human-environment interactions in the Maya Lowlands.


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AFFILIATIONS
[1]Posgrado en Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, Ciudad de México, México
[2]Department of Earth Sciences, Indiana University-Purdue University, Indianapolis, USA
[3]Centro de Geociencias, Universidad Nacional Autónoma de México, Queretaro, México

CONTACT
Alejandra Rodriguez-Abaunza: glarodri@iu.edu


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# Speleothems as a novel tool to elucidate human–fire–ecosystem dynamics in tropical Australian savannas

Elena Argiriadis[1,2], R.F. Denniston[3], S. Ondei[4] and D.M.J.S Bowman[4]

**Fire–climate–human relationships in Australian tropical savannas are poorly understood in pre-industrial periods, particularly at centennial to millennial time-scales. Stalagmites from a cave in the Kimberley region hold the potential for high-resolution paleofire reconstruction from pyrogenic organic compounds spanning these timescales.**

### A need for novel, high-resolution paleofire records in Australian tropical savannas

The history of human management of fire in Australia dates to at least 50 kyr BP (Wurster et al. 2021). However, existing paleofire reconstructions are sparse, both temporally and spatially heterogeneous, and often poorly resolved. This limits our ability to assess the relative impacts of climate and Aboriginal land and fire management on ecological change. Nonetheless, long-term human influences on vegetation and fire frequency are widely demonstrated (Vigilante et al. 2009). At the end of the 18th century, European settlers in southeastern Australia modified interactions between natural drivers of fire and Indigenous management. This led to changes in patterns of fire regimes, which likely contributed to the decline of land mammals and fire-sensitive plants observed throughout the country (e.g. Bowman et al. 2022; Woinarski et al. 2015).

In the fire-prone tropical savannas of northwestern Australia, the lack of long-term, high-resolution paleofire reconstructions is particularly acute. This is due to a scarcity of permanent water bodies and other undisturbed depositional environments suitable for the preservation of biomarkers or paleoecological proxies, such as charcoal and pollen (Wurster et al. 2021). For this reason, exploring the potential of novel, highly resolved, and stable archives is of increasing interest.

Stalagmites from limestone caves are a widely used paleoclimate archive, given that they can grow continuously for thousands of years, resist alteration, enable the use of precise dating methods, and provide high-resolution paleoenvironmental information through different proxies. Stable isotopes of oxygen and carbon, along with trace elements (e.g. Mg, Sr, U), are the main geochemical proxies used in speleothems for paleoclimate reconstruction, most notably paleomonsoon reconstruction (Denniston et al. 2016). The study of organic compounds (e.g. lipids, phenols, and aromatic hydrocarbons) in speleothems is less well developed, despite their potential to preserve paleoenvironmental signals unattainable by inorganic compounds (Blyth et al. 2016).

Caves exist across many parts of Australia, including the tropical areas. An extended, exposed limestone area (Fig. 1) is present in the Kimberley region of northwestern Australia, where the richness in rock art sites documents early human settlement, with some of the oldest paintings dating back to 40 kyr BP. Here, aboriginal management based on localized small-scale burning is believed to have allowed fire regulation and the conservation of fire-sensitive flora and fauna, in contrast with European practices promoting further burning and ecological losses (Yibarbuk et al. 2001). Our research aims to extract records of paleofire activity from Kimberley stalagmites, at near annual resolution, to shed light on complex fire–climate–human relationships in the last millennium, when this abrupt shift in the fire-ecology equilibrium occurred.

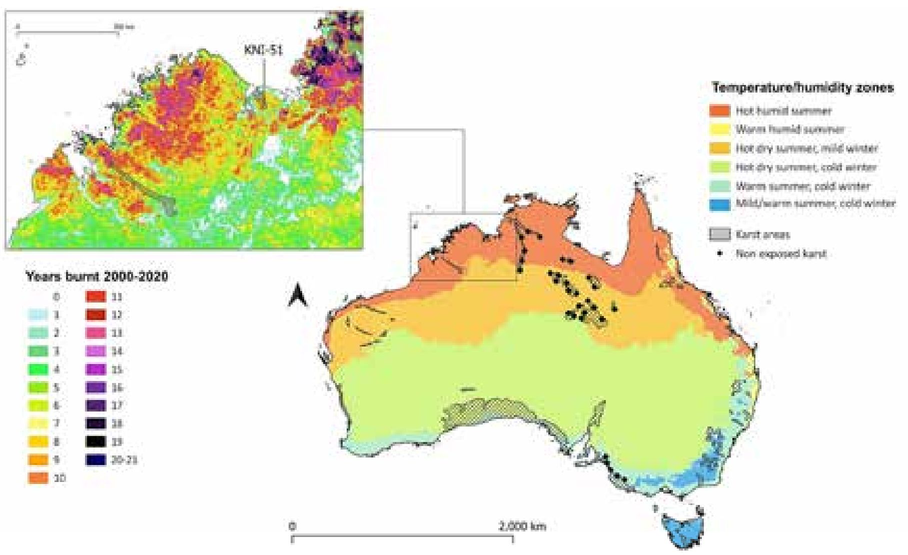


**Figure 1:** Australian climate zones (source: Australian Government Bureau of Meteorology, bom.gov.au) with karst areas distribution (source: World Karst Aquifer Map, whymap.org). Kimberley region with fire frequency and cave KNI-51 location (source: NAFI, North Australia & Rangelands Fire Information, firenorth.org.au).

### Fire proxies in speleothems

Paleofire reconstruction from stalagmites is currently taking its first steps, and is rapidly accelerating, as demonstrated by recent studies where Holocene fire activity in different regions worldwide was investigated through inorganic and organic geochemical proxies. For instance, McDonough et al. (2022) associated peaks in P, Al, Zn, and Cu in a southwest Australian stalagmite to known fire events and prescribed burns, while Homann et al. (2022) related traces of the organic compound levoglucosan in a stalagmite from California to hydroclimate and fuel availability that promoted changes in early Holocene fire activity.

Previous work by Argiriadis et al. (2019) presented a method for the analysis of trace polycyclic aromatic hydrocarbons (PAHs) and *n*-alkanes in stalagmites. These organic compounds reflect biogeochemical processes occurring at the land surface, in the soil, and in the cave. PAHs are primarily related to combustion of biomass, while *n*-alkanes, with their potential for vegetation reconstruction, provide information on fuel availability and composition. These target organic molecules are carried into the underlying cave by infiltrating water, and finally incorporated into speleothems; thereby, creating the potential for speleothems to serve as novel paleofire archives.

PAHs are organic molecules composed of two or more fused aromatic rings and result from incomplete combustion of organic materials. According to fuel and combustion conditions, a wide range of PAHs are associated with biomass burning. Immediately after fires of moderate intensity (200–400°C), abundance of light and medium molecular weight (LMW and MMW, respectively) compounds are elevated in burnt soils, while high molecular weight PAHs (HMW) are rare

 

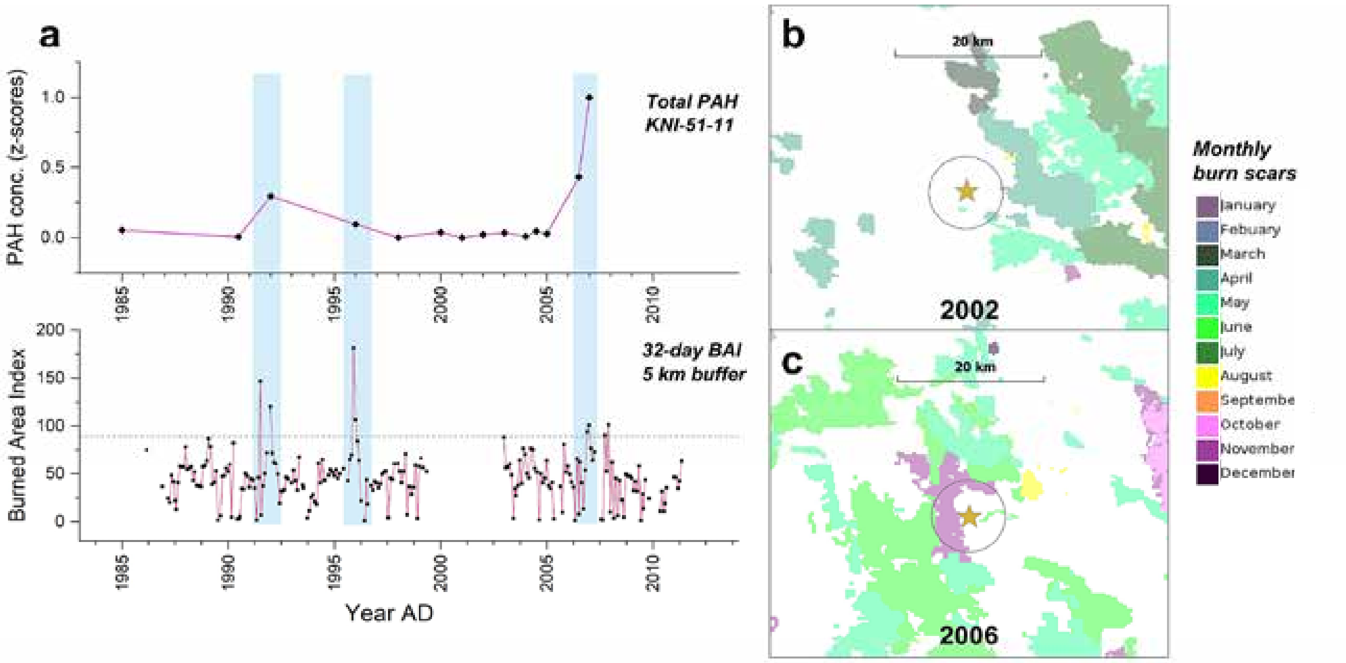


**Figure 2: (A)** Total PAH concentrations (z-scores) from stalagmite KNI-51-11 (top), and 32-days composite of the Burned Area Index within a 5 km radius around the cave (bottom). **(B)** Monthly fire scars (areas of blackened land surface following vegetation fires identified through MODIS 250m satellite imagery) in the cave area in year 2002, and **(C)** in 2006 (source: NAFI, North Australia & Rangelands Fire Information, firenorth.org.au).

to absent (Rey-Salgueiro et al. 2018). HMW PAHs are generally only produced at temperatures higher than ~500°C and are, thus, associated with fossil fuel combustion or very intense fires of woody material (Wang et al. 2017). PAHs are highly persistent in the environment but have generally low concentrations in natural waters due to their low solubility, while soil PAHs are, for the most part, adsorbed onto organic matter-specific sites.

To date, the only known attempt to use PAHs for stalagmite fire reconstruction was performed by Perrette et al. (2008), although the study faced some difficulties due to the complex nature of thick soils and depth of the cave, and, thus, did not yield conclusive paleoenvironmental information. In contrast, cave KNI-51, located in the Kimberley region (tropical northwestern Australia) (Fig. 1), appears to be an ideal setting for the rapid transportation of organic compounds from the land surface to the underlying cave, given that it is a shallow location, covered by thin soil, and permeable and fractured limestone. Stalagmites at cave KNI-51 are also well-suited for this work, as they show high growth rates (1–2 mm $yr^{-1}$) and yield extremely high precision $^{230}$Th dates (2 SD errors = ±1 year over most of the last century), which together offer high (1–3 yr) temporal resolution for PAH measurements.

We analyzed PAHs in three aragonite stalagmites from cave KNI-51. The stalagmites grew during different intervals of the last millennium, and include one that spans most of the period between 1750–2009 CE (KNI-51-11). This time interval encompasses the arrival of European pastoralists in the Kimberley region in the late 19th century.

**Comparison with satellite data**

PAH concentrations in the interval between 1984 and 2007 were compared with the Burned Area Index (BAI), a satellite-derived spectral index obtained from near-infrared reflectance (Chuvieco et al. 2010), computed through Google Earth Engine (GEE) using Landsat 5 Collection 1 Tier 1 images. High normalized PAH concentrations in stalagmite KNI-51-11 coincide with values in the 32-day BAI composite within a 5 km radius around the cave ≥89, which corresponds to the threshold identified by Martin et al. (2005) as indicative of burned areas (Fig. 2). Although differences in resolution between the BAI and PAH records must be considered (BAI composite is given here with a 32-day frequency, while average PAH resolution, although remarkable for a stalagmite record, is 1.6 yr), together with dating uncertainties, the stalagmite PAH record shows potential to capture the signal from bushfires occurring close to the cave, especially in the late dry season (September–November), as shown in high resolution fire-scar maps (Fig. 2). Although preliminary, this finding is a first indication of the validity of our method for long-term fire reconstruction.

**Future work**

As the use of speleothems as a paleofire proxy is in its infancy, several important tests are underway. First, we continued to analyze coeval stalagmites from the same cave to assess the degree of replication in PAH values and trends. Second, during cave floods events, stalagmite caps are coated with sediment, some of which is incorporated into the stalagmite when flood waters recede and stalagmite growth resumes, thus possibly acting as an additional source of organic compounds to the cave. Defining contributions of flood sediment to measured PAH abundances and distributions is critical to define the paleofire signal. Third, the transport of PAHs from the land surface to the cave is not well understood, so a prescribed burn and irrigation experiment will soon be performed to address this and related questions. Finally, contributions of organic compounds from regional oil fields, while extremely unlikely, will be examined as a potential source of contamination through analysis of benzene polycarboxylic acids (BPCA).

AFFILIATIONS

[1]CNR-ISP, Institute of Polar Sciences, National Research Council of Italy, Venice, Italy
[2]Department of Environmental Sciences, Informatics and Statistics, University of Venice, Italy
[3]Department of Geology, Cornell College, Mount Vernon, USA
[4]School of Natural Sciences, University of Tasmania, Sandy Bay, Australia

CONTACT

Elena Argiriadis: elena.argiriadis@cnr.it

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# Pre-Columbian legacy and modern land use in the Bolivian Amazon

Umberto Lombardo[1,2]

**Here, I present a case where large extensions of seasonal wetlands in the Bolivian Amazon are being transformed into monoculture deserts. Yet, farmers can argue that their practices do not differ from pre-Columbian landscape transformations around 1000 years ago.**

One of the reasons for studying the past is that we can learn from it. Learning about past human–environment interactions can guide and inspire us towards adopting more sustainable practices in the face of anthropogenic global warming and environmental change (Boivin and Crowther 2021). However, past models of huma–environmental interactions cannot always be transferred into our modern societies, as environment, technological and cultural contexts change across time and space.

**The Monumental Mounds Region**

The Monumental Mounds Region (MMR), in the center of the Llanos de Moxos in the Bolivian Amazon, hosts hundreds of monumental mounds built by the Casarabe culture between roughly 2000 and 500 years ago (Lombardo and Prümers 2010; Prümers et al. 2022). These mounds are human-made architectural structures that can reach up to 20 meters in elevation and cover up to 20 hectares. They are the remains of the only example of agrarian-based, low-density urbanism in pre-Hispanic Amazonia (Prümers et al. 2022). Monumental mounds have a hierarchical organization and are connected by hundreds of kilometers of canals and causeways. This level of social complexity would not have been possible without a very productive agricultural system. Pollen records from San José Lake (Whitney et al. 2013) and microbotanical remains from pottery (Dickau et al. 2012) suggest that maize was an important element of the diet at that time.

Nowadays, this region is at the forefront of the expansion of the agriculture frontier (Ormachea 2021), witnessing a sharp transition from cattle ranching to soy and rice production. This transition is having a large impact on the savanna, as land use is shifting from grazing to intensive, mechanized agriculture. Figure 1 shows the current land cover (based on Copernicus Sentinell-2 data, retrieved from Scientific Data Hub, Level-2A processed by ESA) of the central part of the MMR, with almost half of the savanna formerly used for cattle grazing now being cultivated. While slash and burn agriculture has been a common practice by Indigenous peoples in the forested areas, it is the first time since the collapse of the Casarabe culture that these savannas are being cultivated (Killeen et al. 2008).

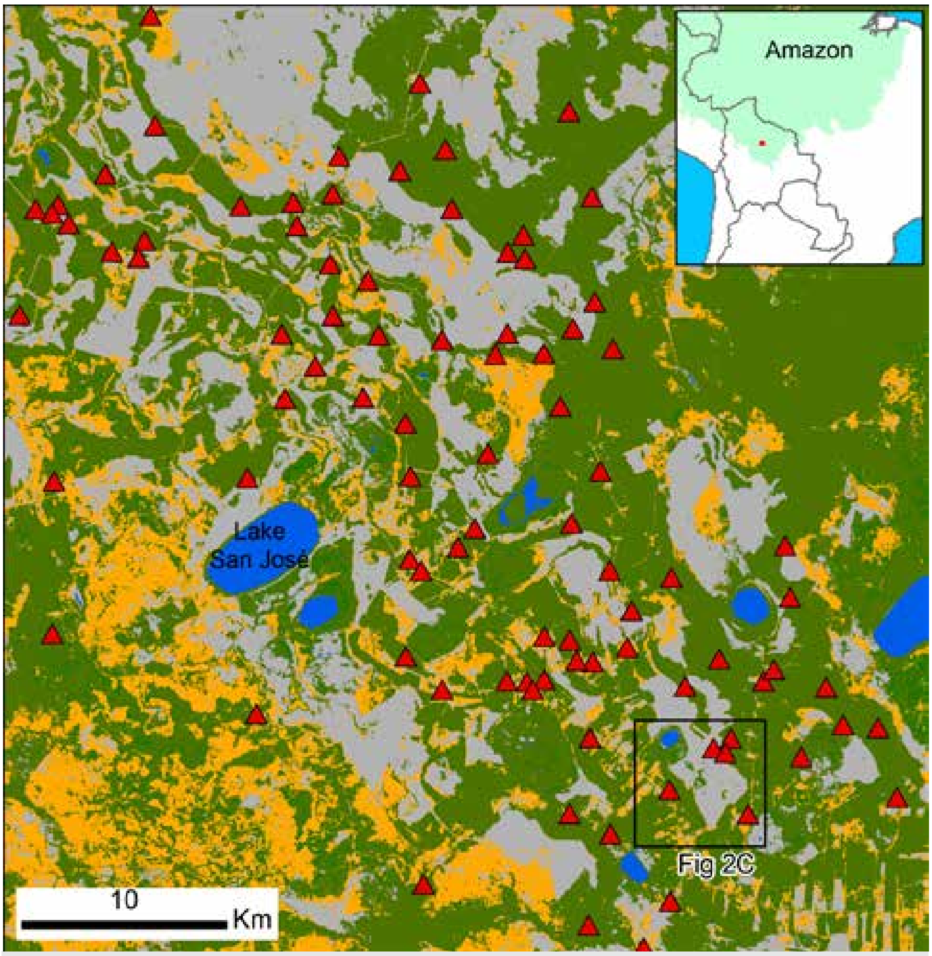


**Figure 1:** Land-cover classification of the central part of the Monumental Mound Region. The orange areas are covered with grass, and mostly represent open and dry savanna under cattle-ranching and deforested areas. The green is evergreen vegetation; mostly forest growing over the fluvial levees. The gray is bare soil; mostly recently plugged savannas for agriculture. Red triangles are monumental mounds.

**Pre-Columbian agriculture in the MMR**

When compared with the rest of the Amazon basin, the MMR has high agricultural potential because it is established on relatively recent fluvial sediments. Thousands of years ago, the Río Grande, a large river that today flows into the Mamoré River from east to west, followed a different course: it went from south to north, passing across the very area where the MMR is located. Due either to a change in climate conditions (Mayle et al. 2000) or a tectonic uplift (Lombardo 2014) the Río Grande started to repeatedly change its course, creating a delta-like environment at around 4 kyr BP. During this period of avulsions (i.e. rivers changing course because of floods outpacing natural margins or fluvial levees), the Río Grande deposited a huge amount of Andean sediments in what is now the MMR. Here, the Río Grande created two types of relief; a lens of sediments up to four meters thick over an area of approximately 2600 km$^2$ that formed a sedimentary lobe, and a number of fluvial levees (Lombardo et al. 2012). The modern land cover of the MMR is the result of these geomorphological processes. Most of the sedimentary lobe is now covered by seasonally flooded savanna established over backswamp deposits, while the paleo-levees, which remain above the water level almost the whole year, are forested (Fig. 1). The sedimentary lobe provided relatively fertile and better drained soils than the rest of the Llanos de Moxos (Lombardo et al. 2013) and its topography determined the settlement patterns in the MMR. In fact, the monumental mounds were always established along paleo-channels, often along the inner part of the meanders (Lombardo and Prümers 2010). Despite the fact that the formation of the sedimentary lobe in the MMR brought about several agricultural benefits, the paleo-channels also created conditions of poor drainage. Fluvial levees enclosed the

 

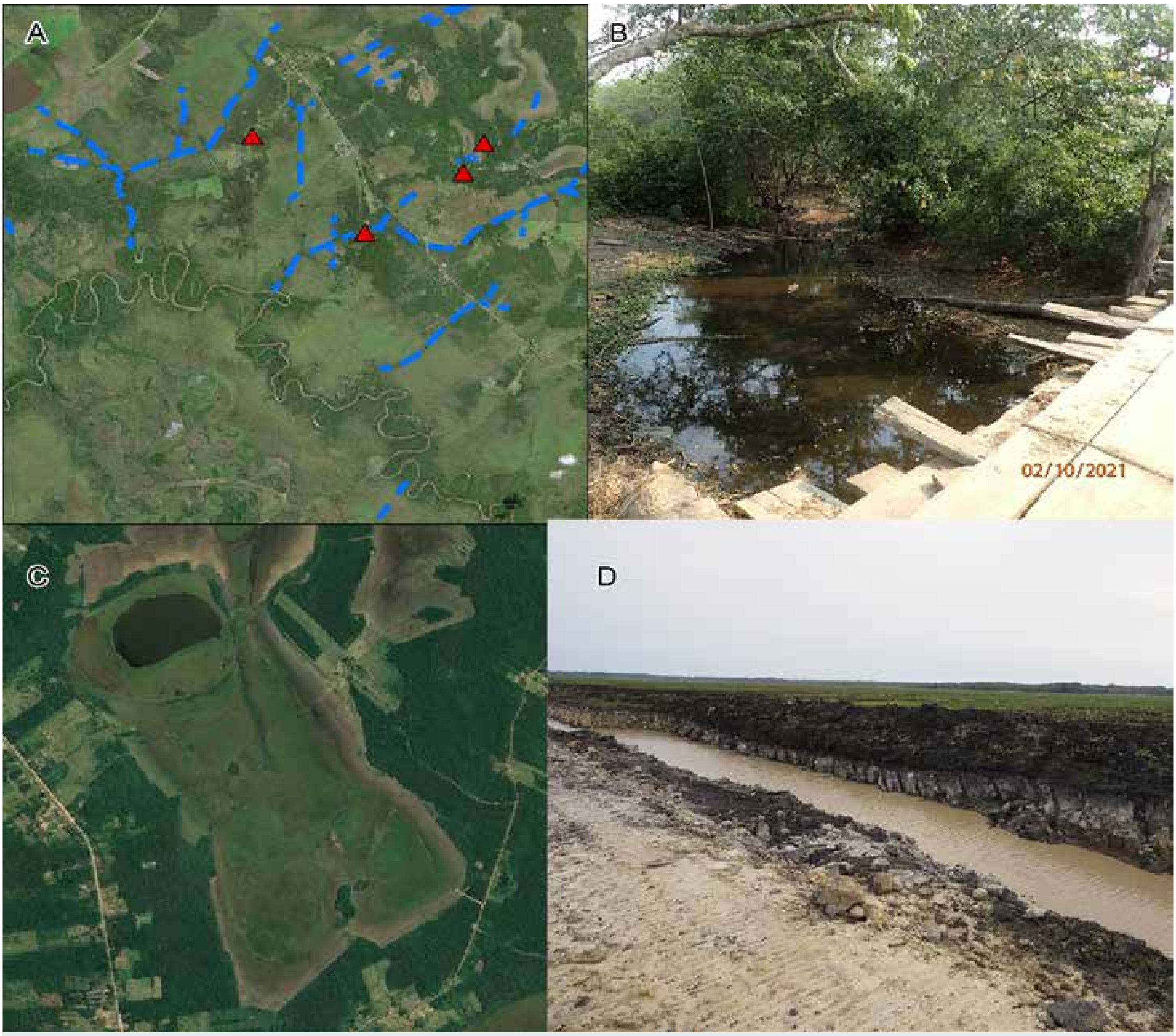


**Figure 2:** Land-use change in the Monumental Mound Region. **(A)** Pre-Columbian drainage canals (blue) take water from the savanna to the Ibare River (Lombardo et al. 2012). **(B)** Photo of a still functioning pre-Columbian drainage canal. The canal is six meters wide and three meters deep. **(C)** Satellite image taken in 2021. The brownish/gray areas along the forest shows savanna being cultivated. In 2022 (see Fig. 1), the whole savanna was plugged and planted with soybeans. **(D)** Modern drainage canal excavated in 2022, draining the savanna in (C). Note that the modern canal is cutting through a pre-Columbian one, visible as the black profile along the right margin of the canal.

patches of backswamp floodplain, resulting in ponding and pronounced waterlogging. Thus, in order to make full use of the MMR's agricultural potential, the Casarabe culture transformed the landscape through the construction of a drainage system (Lombardo et al. 2012). This was achieved by digging canals that cut through the paleo-levees (Fig. 2a) and connected the savannas to the rivers. In so doing, the Casarabe culture managed to speed up the drainage of the savannas at the end of the rainy season and made it possible to farm in the savanna.

**Modern agriculture in the MMR**

Even though most of the pre-Columbian drainage canals have been partially infilled with sediments, the overall network still plays an important role in speeding up drainage at the end of the rainy season. Figure 2b shows a picture of an active pre-Columbian drainage canal. Over the past years, this partially functioning drainage system has allowed farmers to cultivate the outer part of the savannas, along the border with the forest where the elevation is higher, while the inner part of the savanna has been left intact (Fig. 2c). By doing this, modern farmers have taken advantage of a pre-Columbian legacy.

More recently, however, farmers have started to cultivate the whole savanna. By excavating new drainage canals (Fig. 2d), farmers are now draining the deeper part of the savanna. The peat accumulated over the last few centuries is now drying, and it will be later burnt with the consequential release of tons of $CO_2$ into the atmosphere. What in pre-Columbian times was a collective effort of landscape transformation and management that probably took decades to implement, is now a large-scale, land-use change that only requires a few months of intensive tractor use. Yet, objectives and results are basically the same: draining the wetlands to make space for agriculture.

AFFILIATIONS

[1]Institut de Ciència i Tecnologia Ambientals (ICTA-UAB), Universitat Autònoma de Barcelona, Spain

[2]Department of Prehistory, Universitat Autònoma de Barcelona, Spain

CONTACT

Umberto Lombardo: umberto.lombardo@uab.cat

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# Interactions between past societies and environmental change in the Lake Titicaca region (tropical Andes)

Christophe Delaere[1], S. Guédron[2] and S.C. Fritz[3]

**Over the millennia, complex and elaborate cultures have emerged in the Lake Titicaca region. Recent archaeological evidence and new environmental reconstructions spanning the last ~4500 years have enabled us to explore the interactions between cultural developments of past societies and the changing environment.**

The history of societies is influenced by interactions between humans and their environment. This is particularly the case for communities of the high tropical Andes, who repeatedly experienced large amplitude changes in climate and the surrounding landscape.

Here we present recent underwater archaeological evidence and paleoenvironmental reconstructions compatible with archaeological timescales. We then focus on identifying and exploring the relation between major environmental changes and cultural innovations in the Lake Titicaca region to decipher potential relationships.

## Lake Titicaca sediment: An archive of past climate change and human activities

Lake Titicaca's sediment record preserves both natural variability and cultural-related signals (Guédron et al. 2021). Multiple studies have reconstructed water-level variability from diverse proxies (e.g. sedimentology, geochemistry, microfossils) and inferred fluctuations in moisture balance at the regional scale (Baker et al. 2001). In general, the temporal resolution of existing paleoenvironmental studies in Lake Titicaca was not high enough to be compared with archaeological studies.

A relatively novel approach in the last decade has been underwater archaeological studies which enabled the refinement of the dating of sediment layers at the archaeological timescale by the analysis of ceramic remains found buried in the sediment. For the first time, underwater archaeological remains and artefacts in Lake Titicaca's sediment have shed light on the impact of water-level variation on human occupation of the land, and revealed the presence of an unknown, and now flooded, cultural landscape (Delaere 2017; Delaere 2020; Delaere and Guédron 2022) (Fig. 1a–b). Extensive underwater excavations integrating paleoenvironmental approaches have disclosed the presence of pre-Hispanic port areas (Fig. 1c–d), coastal workshop sites dedicated to manufacturing activities (e.g. leather, stone, and wool) (Fig. 1e), and pastoral and human areas that are currently submerged (Fig. 1f). Ritual offerings have also been identified underwater (Delaere et al. 2019; Delaere and Capriles 2020). These cultural artefacts differ, however, from other remains as they are intentional tributes, and not linked to environmental alteration events. Today, more than 25 underwater archaeological sites, mainly submerged coastal settlements, have been explored in Lake Titicaca (Fig. 1b) using underwater geoarchaeological tools (underwater excavations and sediment cores) to better understand the historical interactions between humans (e.g. settlement dynamics), and their changing environment (i.e. transgression and regression of the lake). Remnants of both the anthropogenic and natural ecosystems are perfectly interconnected and preserved in the lake sediments.

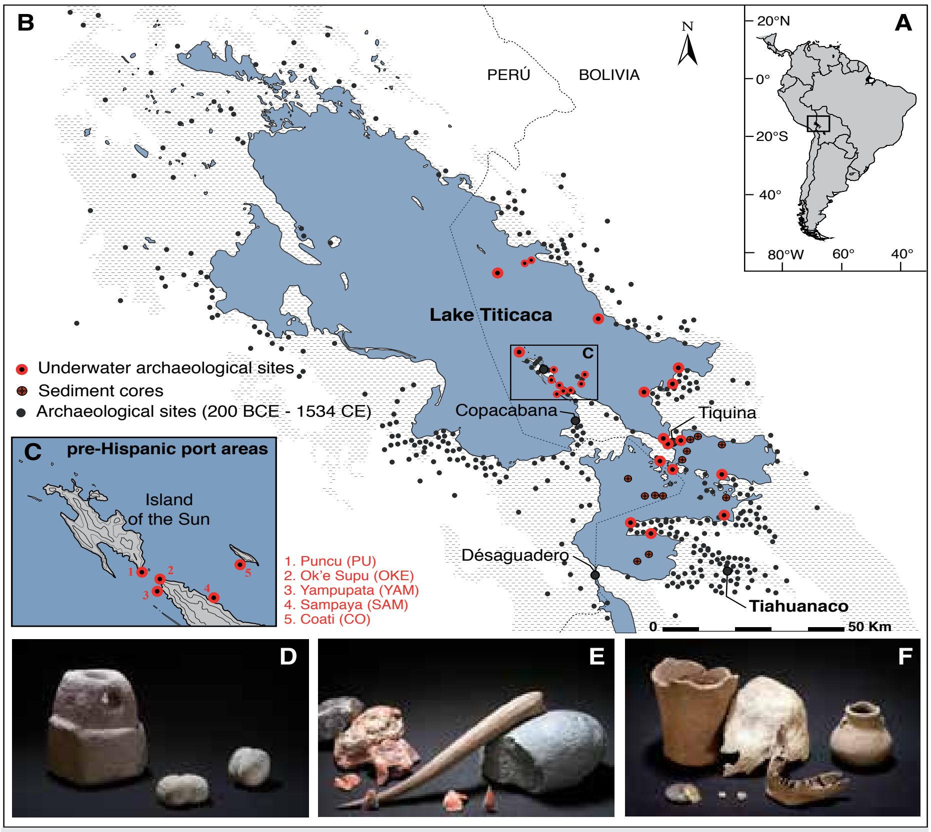


**Figure 1: (A)** Location of Lake Titicaca (16°S, 69°W) in the tropical Andes. **(B)** General map of Lake Titicaca with the location of the archaeological sites surveyed since 1950 (black circles), the underwater archaeological sites surveyed between 2012 and 2022 (red circles), and the sediment cores sampled between 2014 and 2017 (dark orange circles). The coastline is defined as the average modern lake level (3810 masl). The civic-ceremonial center of Tiahuanaco is located in the southern part of the basin. **(C)** Location of five pre-Hispanic ports discovered between Copacabana Peninsula and the Islands of the Sun and the Moon. **(D)** Pre-Hispanic navigation artefacts (anchor and ballast stones) discovered underwater at Puncu (PU). **(E)** Remains of tools belonging to a Tiwanaku stonecutter's workshop discovered underwater in Ok'e Supu (OKE). **(F)** Remains of a pre-Tiwanaku tomb discovered underwater at Puncu (PU) (Photo credit images D-F: T. Seguin).

## Environmental changes and cultural responses at Lake Titicaca

The combination of geological and archaeological methods has enabled the development of a new model of Lake Titicaca's lake level variations at a resolution compatible with archaeological timescales (Fig. 2) (Guédron et al. 2023). Due to the gentle slopes of the southern Lake Titicaca basin, variation in lake-level of a few meters results in substantial changes in the exposure of surrounding land. Hence, over the past four millennia, human communities have witnessed multiple transgressions and regressions (up to ~5 m) of Lake Titicaca that have submerged, or opened areas for settlement and agriculture (Fig. 2b) (Delaere and Guédron 2022). Yet, ancient native populations in the lake basin undoubtedly had a well-developed knowledge of the local ecosystem and

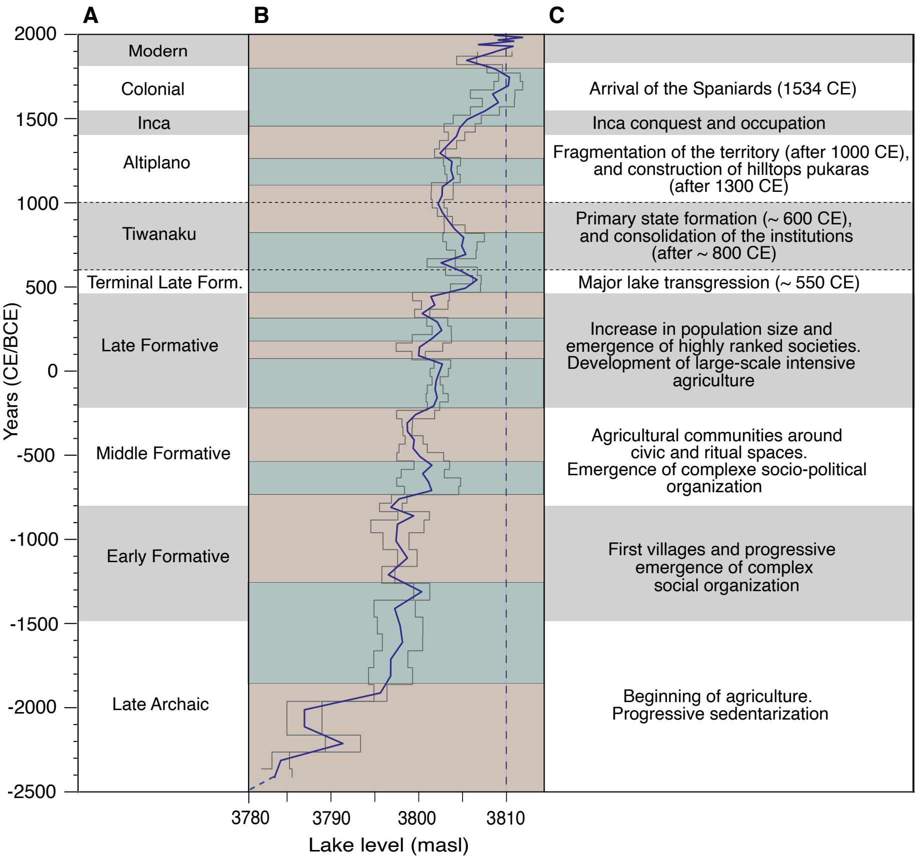


**Figure 2: (A)** Major cultural periods (in gray and white) defined by archaeology. **(B)** Lake Tititcaca's average lake level with cumulative error (gray envelope) of the model (Guédron et al. 2023). Shaded green (beige) background lines represent intervals of high (low) lake level from the averaged modeled lake-level curve. **(C)** Cultural challenges or innovations typical to each cultural period.

diversified the exploitation of resources in response to climate variability. In the case of agriculture, the succession of dry and wet periods induced long-term cultural responses that illustrate the great resilience of human communities (Bruno et al. 2021).

Increased precipitation led to the gradual rise in lake level from 2400 BCE onward (Fig. 2b). This climatic and environmental shift induced cultural changes and innovations within Lake Titicaca's human communities. Some of them coincided with significant increases in lake-water level, such as the development of agriculture ca. 2000 BCE (Bruno 2014), farming communities organized around civic-ceremonial centers ca. 800 BCE (Hastorf 2003), or the first "fortified" cities, named pukaras, at the top of the slopes of the drainage basin ca. 1300 CE (Arkush 2008) (Fig. 2).

The emergence or disappearance of components of the Andean cultures were complex responses to diverse types of change. Some natural events promoted cultural responses in the short term, but cultural development was ultimately influenced by a multifactorial relationship that included both natural and societal criteria. At Lake Titicaca, the progressive rise in the lake level over the last ~4500 years was accompanied by cultural changes observed in the archaeological evidence (sedentarization, population expansion, emergence of social complexity, etc.). This is the case for the rapid rise of the lake during the Terminal Late Formative period (ca. 550 CE; Fig. 2b), which flooded large areas of arable land, and probably forced populations to abandon land near the shore, and take refuge in higher elevated regions (Guédron et al. 2023). These environmental changes had consequences for local societies. The emergence of the Tiwanaku culture (600 CE) that succeeded this natural event (550 CE) is the product of several factors (e.g. Marsh et al. 2019). At that time, the civic-ceremonial center of Tiahuanaco, a small center of local power south east of Lake Titicaca (Fig. 1b), had reached sufficient social, economic, and political maturity to take advantage of environmental and demographic changes, and establish a position of regional power over the entire lake basin in less than half a century. Later, around 800 CE, the destruction and reconstruction of part of the civic-ceremonial core of Tiahuanaco (Couture and Sampeck 2003) was a new, decisive turning point that promoted the "emergence of an elite class and the crystallization of a rigidly defined social hierarchy in Tiwanaku" (Janusek 2004). At the same time, the level of Lake Titicaca began to decline, which continued until the end of the Tiwanaku period (Fig. 2). Although these last two events were synchronous, the progressive decrease in the water level of the lake did not have irreversible consequences between 800 and 1000 CE due to the persistence of the Tiwanaku culture.

**Human-environment interactions across a spectrum of environmental scenarios**

The interaction between past societies and climate change has been the focus of research in the Andes for decades. The reevaluation of Lake Titicaca's society and ecosystem allows us, with a new combination of approaches, to explore the nuances of human-environment interactions across a spectrum of environmental scenarios (high and low lake level). Prolonged drought, due to natural climate change, can lead to technological innovations in agricultural land management (e.g. irrigation, canalization, and raised fields), whereas lake transgressions (environmental alterations during highstand phases) involving the loss of large agricultural areas may induce cultural shifts (social and economic structure), which also affect land use and management. The time factor is important in the study of the relationship between natural and cultural signals. We can perceive, for the first time, the nuance between the short-term cultural responses (e.g. the exodus of a population that must abandon the flooding of a territory) and long-term cultural responses (reorganization of political, economic and religious institutions). The new chronological resolution allows us to identify different crisis situations in land management (natural action vs cultural reaction), in particular that of 550 CE, but the effective cultural response, whether positive (resilience) or negative (collapse), is calculated over time. Major regional cultural changes (Fig. 2c) coincided with significant rises in Titicaca's lake level (Fig. 2b, green shading) but with an apparent delay of 50 to 200 years. This delay reflects the cultural long-term response to environmental alterations.

AFFILIATION

[1]Centre de Recherches en Archéologie et Patrimoine, Université libre de Bruxelles (ULB), Brussels, Belgium
[2]Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre, Grenoble, France
[3]Department of Earth and Atmospheric Sciences, University of Nebraska, Lincoln, USA

CONTACT

Christophe Delaere: delaerechristophe@gmail.com

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# Past synchronies, asynchronies, and collations between naturally and anthropogenically driven changes in northern Chile

Antonio Maldonado[1], C. Méndez[2] and M. Uribe[3]

**How climate change influenced societies in the past is a key issue facing ongoing and future climate change. Past human society–environment relationships in northern Chile provide evidence of different ways to cope with climate change in extreme environments.**

Either naturally or anthropogenically driven, climate changes could lead to large environmental changes and, hence, affect socio-economic activities at different temporal scales. Nowadays, as in the past, the world is facing these effects as climate changes occur, impacting human societies in different ways and forcing them to adapt, resist, or migrate.

Currently, in Chile, this situation is critical because of the scarcity of water following the decreasing precipitation trend. Its effects are quite clear, including the drying of high Andean wetlands and lakes, the lowest historical stands of water reserves, loss of vegetation cover, and the abandonment of productive land. However, northern Chile has experienced a series of climatic changes at millennial to centennial timescales. How did human societies cope with these past changes? Did some of them make adjustments in response to climatic changes? If yes, were those responses synchronous with the climatic changes? These and other questions can be answered through interdisciplinary research using geosciences and archaeology across sites in northern Chile.

In this article, we focus on two main regions (Fig. 1): Pampa del Tamarugal, in the center of the Atacama Desert (21°S), which reveals a fascinating Late Holocene development of agricultural societies in the driest desert of the globe; and Los Vilos, located in the semi-arid coast of subtropical Chile (32°S), which was a region inhabited by hunter-gatherers specialized in exploiting marine resources throughout the Holocene.

**Climatic setting**

The Pampa del Tamarugal records near zero precipitation throughout the year, and surface runoff is only associated with extreme rainfall events in the highlands. Precipitation sourced from the east and associated with the South American summer monsoon falls in the Andean highlands (Altiplano) (Fig. 1) and infiltrates the land, becoming subterranean discharge. Once in the lowlands, the subterranean water table reaches the surface.

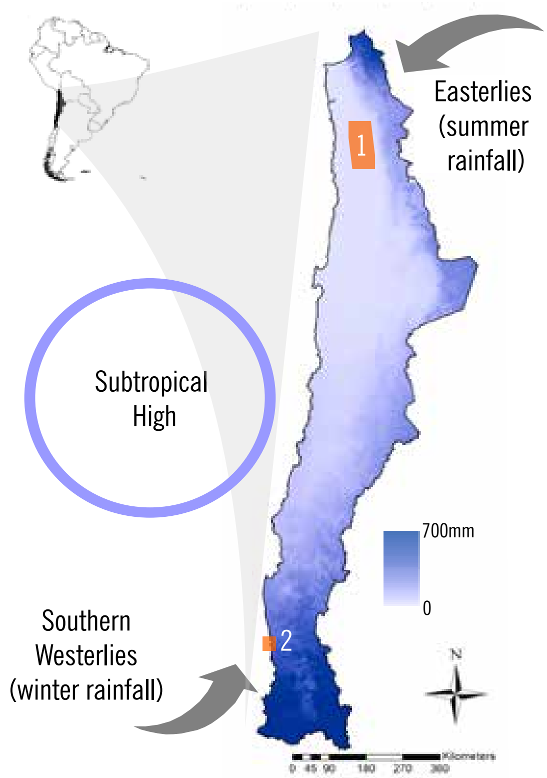


**Figure 1:** Map of the study area showing annual precipitation and the main climatic features of northern Chile. The orange rectangles show the study sites of Pampa del Tamarugal (1) and Los Vilos (2).

In contrast, on the semiarid coast of Chile (32°S), precipitation is around 200 mm/yr and represents a marked seasonality, with winter-centered rainfall controlled by the Southern Hemisphere Westerlies (SHW) (Fig. 1). River discharge shows a fluvio-nival pattern with increasing amounts in winter and spring.

**Farmers in the arid Atacama Desert**

The archaeological record of Pampa del Tamarugal shows abundant evidence of hunter-gatherer societies since 11 kyr BP (Fig. 2a). These groups settled along active springs, canyons, and wetlands in the center of the desert until 9.5 kyr BP, when conditions became so dry that only a few sites were occupied during the Mid-Holocene (Santoro et al. 2017). It was not until the Late Holocene (after 3 kyr BP) that these areas were again occupied, though showing quite different characteristics. A marked transitional period from exclusively hunter-gatherer societies to the development of agriculture, a sedentary lifestyle, and a high degree of social complexity occurred in the Pampa del Tamarugal at around ~2.5–1 kyr BP (the Formative Period; Fig. 2a). A vast array of diverse archaeological evidence recorded over hundreds of kilometers reveals the development of a network of multiscale settlements. These include villages with monumental public areas and intensive and extensive agriculture as shown not just by the cultivation plots, but by sophisticated technologies to manage surface water (Adán et al. 2013; Urbina et al. 2018; Fig. 2a). The development of such complex societies in the core of the desert (2000–1000 masl) cannot be explained unless this happened under completely different climatic conditions than those of today.

Pollen records from rodent middens collected at 3500 and 3750 masl at 21°S were used to reconstruct past environmental condition changes (Fig. 2a; Maldonado and Uribe 2015). The rodent midden pollen record at 3500 masl reflect drier conditions than present at around 3.7 kyr BP, and after 700 yr BP, while wetter conditions occurred between 2 kyr BP and 700 yr BP. On the other hand, the rodent midden pollen record at 3750 masl shows wetter than present conditions at around 10 kyr BP and 2.2–1 kyr BP, drier than present conditions at around 3.5 kyr BP and after 700 yr BP, and a transitional wet-to-dry phase between 1 kyr BP and 700 yr BP.

 

As for the archaeological record, central villages of the Formative Period started at around 2.3 kyr BP and were occupied until at least 1 kyr BP. By that time, villages of the Late Intermediate Period started growing in higher altitude canyons to the north, following the precipitation gradient. Thus, when integrating the environmental and archaeological evidence of Tarapacá, where water is extremely scarce and critical for survival, there is synchronicity between the occurrence of wetter-than-present conditions and the intensification of settlement and cultivation plots, accompanied by more social complexity during the Formative Period (Uribe et al. 2020). Besides, the development of villages at higher and more northern canyons occurred when conditions became transitional towards drier than present, during the Late Intermediate Period.

**Coastal hunter-gatherers of semiarid Chile**

In semiarid coastal Chile, the environment-human relationships are rather different to those in the Atacama Desert, and the key environmental archives for tracing past environmental and climate changes are sedimentary records in coastal swamp forests. Coastal swamps form diverse and densely vegetated hygrophilous small forests in a matrix of semidesert shrublands, and grow in areas where the water-table level reaches the surface. The coastal water-table level is recharged by precipitation falling above 2000 masl that infiltrates and moves underground.

The swamp-forest pollen records show the occurrence of the two most contrasting periods corresponding to the driest interval between ~8–5 kyr BP, and the wettest period starting at 2 kyr BP (Fig. 2b; Maldonado et al. 2010; Maldonado and Villagrán 2006; Méndez et al. 2015). On the other hand, the archaeological record including more than 200 sites (mostly coastal and corresponding to shell middens) reveals an almost continuous presence of humans in the area for the last 13 kyr (Fig. 2b; Méndez and Nuevo-Delaunay 2021).

When integrating the environmental and anthropogenic trends (based on the sum of probabilities of radiocarbon dates, Méndez et al. 2018), both synchronous and asynchronous events are recorded. While people lived along the coast regardless of the environmental conditions, likely due to the permanent supply of marine resources, inland sites show a marked occupation only since 3 kyr BP, when the climate shifted towards wetter conditions, as shown by the pollen records of Laguna Grande (Fig. 2b). The archaeological evidence suggests different mobility and occupation patterns of the coast over time. The initial human presence in the area was coeval with extinct megafauna under slightly wetter conditions than present. The first coastal adaptations at ca. 12 kyr BP reveal an almost permanent presence of settlers, with occasional incursions into the interior, under relatively humid but variable environmental conditions. During the Early Holocene (Huentelauquén Phase II) (Fig. 2), as the environment became drier, the once coastal hunter-gatherers turned their attention to ravine resources, and inland incursions increased. Interestingly, the driest spell of the sequence is associated with a decrease, and almost abandonment of, the coastal settlements between 8.3 and 7.6 kyr BP (Méndez and Nuevo-Delaunay 2021). After this extremely arid phase, settlements were again located along the coast. With the gradual return to wetter conditions, occupation density reached their maximum at 3 kyr BP, either in coastal or inland archaeological records. Finally, with the development of horticulture and pottery at 2 kyr BP (Early Ceramic Period), coastal occupations became less prominent, and groups increasingly occupied the inland under wetter than present conditions, at the expense of the use of coastal landscapes and their resources.

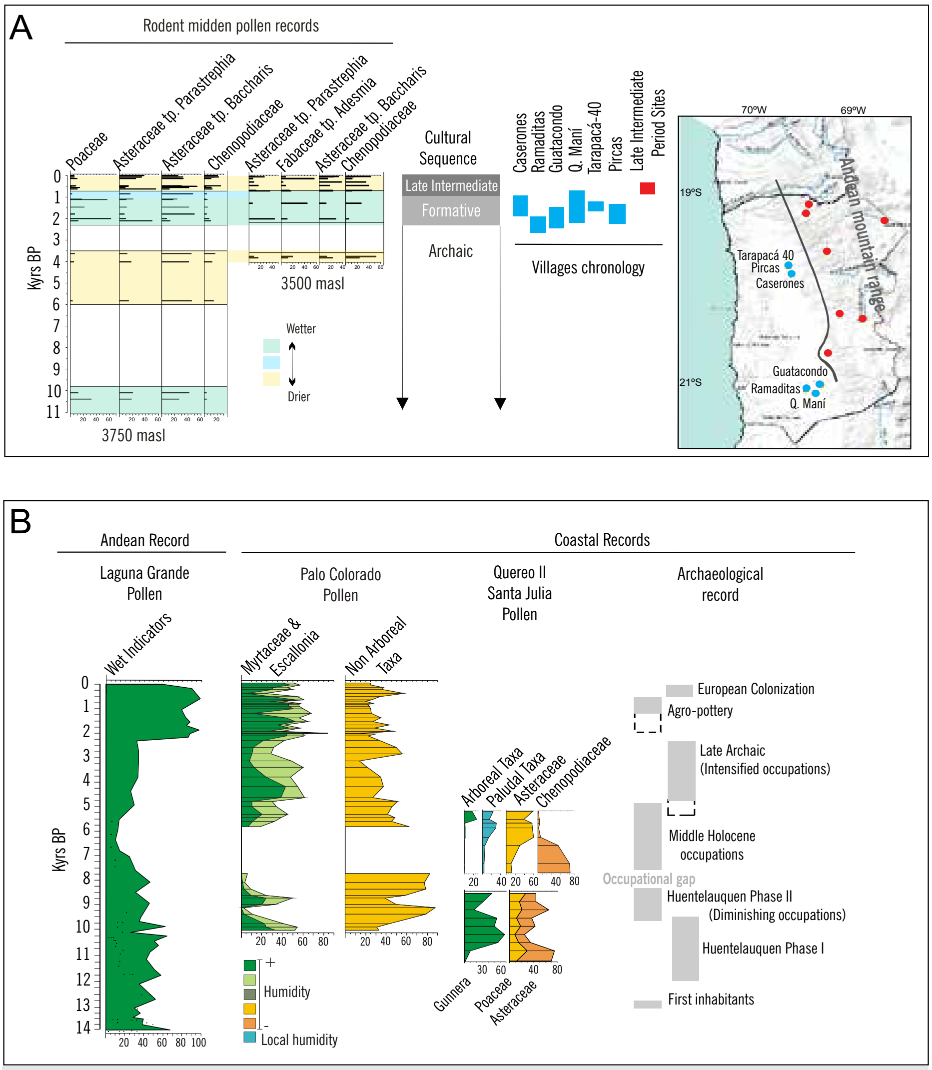


**Figure 2:** Comparison of paleoclimatic records and archaeological sequences in **(A)** the Pampa del Tamarugal (blue dots and rectangles correspond to Formative Period sites and red to Late Intermediate Period sites); and **(B)** Los Vilos areas.

**Final words**

The case studies of human society–environment relationships in northern Chile show that people coped with past climate change at centennial timescales by either technological developments to manage the water, or by occupying sites where resources were independent of the environmental/climatic scenarios. The occupation of alternative sites (inland) or migration (highlands) occurred under the establishment of extremely wetter or drier conditions, respectively.

AFFILIATIONS

[1]Centro de Estudios Avanzados en Zonas Áridas (CEAZA), La Serena, Chile

[2]Centro de Investigación en Ecosistemas de la Patagonia (CIEP), Coyhaique, Chile

[3]Departamento de Antropología, Universidad de Chile, Santiago, Chile

CONTACT

Antonio Maldonado: antonio.maldonado@ceaza.cl

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# Human–environment interactions in South Asian watersheds over the last 100 years: A multi-disciplinary analysis of *talavs*

Atreyee Bhattacharya[1,2,3], J.S. Leonard-Pingel[4], S. Sarkar[5], G. Arora[3], R. Ray[2,3], A. Ambilili[6], A.V. Michelson[7], P.K. Mishra[6], M. Desimone[1], S. Chakraborty[8,9], P. Sabale[10], K. Bajaj[8,11], A. Bhattacharya[12], R. Balaji[1] and A. Bazaz[2]

**Human-made water bodies, called *talavs*, are common features of arid and semiarid regions of South Asia. Multi-disciplinary research into these *talavs* demonstrates untapped potential to investigate the long-term response of coupled human–environment systems to climate fluctuations in these regions.**

Rain-fed watersheds in arid and semiarid regions of South Asia – home to millions, and host to major agricultural and urban centers – are some of the most vulnerable climate hotspots (regions that experience pronounced and well-documented impacts of anthropogenic climate change; Khan and Cundill 2019). Anthropogenic climate change, combined with rapid changes in land-use patterns (e.g. agriculture and urbanization), has degraded natural resources in these watersheds resulting in increased economic stress, social instability and escalating conflict (ASSAR 2018). In order to formulate better solutions to manage water resources in these hotspots, there is mounting demand from both scientists and policymakers for an improved understanding of the relationship between human communities and natural resources, especially under different climate scenarios.

The famous American poet Robert Penn Warren observed, "History cannot give us a program for the future, but it can give us a fuller understanding of ourselves, and of our common humanity, so that we can better face the future." Watersheds in arid and semiarid regions of South Asia, which have witnessed human settlement for millennia, represent a tight coupling of human–environment interactions that have evolved over the *longue durée** in response to a complex interplay of climatological, environmental, cultural and historical events (Ray et al. 2021). However, studies documenting how human societies have responded to water bodies in these climatologically threatened watersheds over the *longue durée* are lacking. Here we explore a unique, but ubiquitous, type of surface water body – human-made surface water bodies called *talavs* – to understand the evolution of human responses to water resources in semiarid climate hotspots of western India during documented periods of climate fluctuations.

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**Longue durée* means "long duration" and is used to describe the effects of events that occur slowly enough to be imperceptible, and allows studies of human history to accommodate climatology, demography, geology, and oceanography (Braudel 2009).

**What are *talavs*? Why and how do we study them?**

In arid and semiarid regions of South Asia, a unique type of surface water body, created by damming tributaries and distributaries of seasonal rain-fed river channels, are ubiquitous. The dammed river channels, colloquially known as *talavs*, are mentioned in archaeological studies (Shanmugasundaram et al. 2017), historical texts and in contemporary policy literature (ASSAR 2018) in relation to water access for the purposes of sustenance, agriculture, communication and urbanization. *Talavs* typically have an area of ~2–5 km$^2$ and catchment areas ~30–100 km$^2$. Owing to their small size and continued presence over the *longue durée*, *talavs* can provide much-needed insights into the nature and causes of evolution of catchment level human–environment interactions under different climate scenarios that are important for policy and planning.

To capture human–environment interactions spanning the lifetime of these *talavs*, we combine a natural sciences approach with a social sciences perspective. The natural sciences approach involves understanding the state of the water bodies today (e.g. by using remote sensing, geophysical surveys, and biogeochemical analyses) and in the past (e.g. by studying similar downcore properties in sediment cores extracted from lake bottoms). The social lens, on the other hand, involves understanding the human use of these water bodies in the past (e.g. by extracting information related to the *talavs* from archived administrative colonial texts) and in contemporary times (e.g. by conducting in-depth interviews with stakeholders). We call this novel, mixed method of studying water bodies "the four-pronged approach".

**Human–environment interactions in semiarid west Indian watersheds**

Semiarid regions of western India that overlie the Deccan Traps, and lie in the rain shadow of the Western Ghats (Sahyadri mountain range) running parallel to the western coast of India, is a well-known climate hotspot (ASSAR 2018, Fig. 1a). *Talavs* are ubiquitous in this region (Fig. 1b). We apply our novel "four-pronged approach" to investigate *talavs* in several catchment areas of our study area, the Bhima watershed (outlined in Fig. 1a). We list some of our observations below.

**(a)** Combining remote sensing, geophysical surveys and downcore analyses (grain size, X-ray fluorescence and radiometric dating), we found that *talavs* serve as sedimentary archives recording erosional patterns in the catchment. The erosional patterns are affected by the local environmental (e.g. vegetation) and geological (e.g. slope) factors within the catchment, and the type

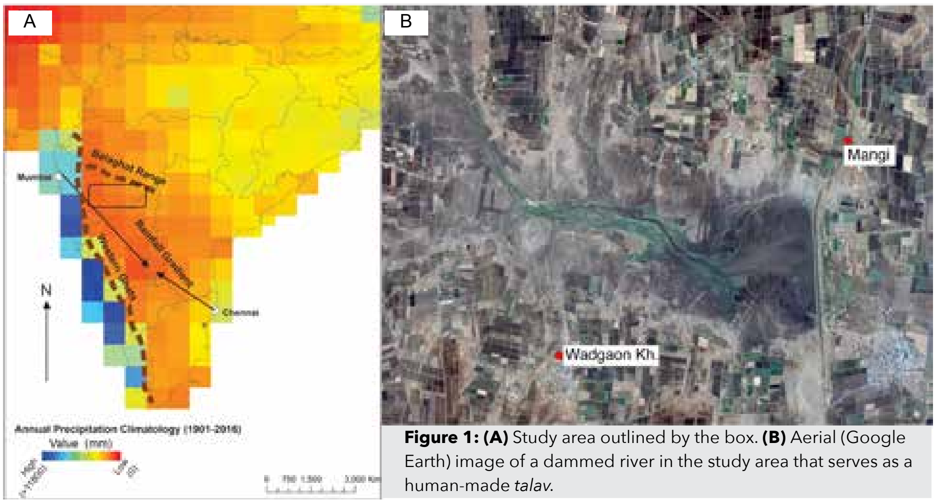


**Figure 1: (A)** Study area outlined by the box. **(B)** Aerial (Google Earth) image of a dammed river in the study area that serves as a human-made *talav*.

 

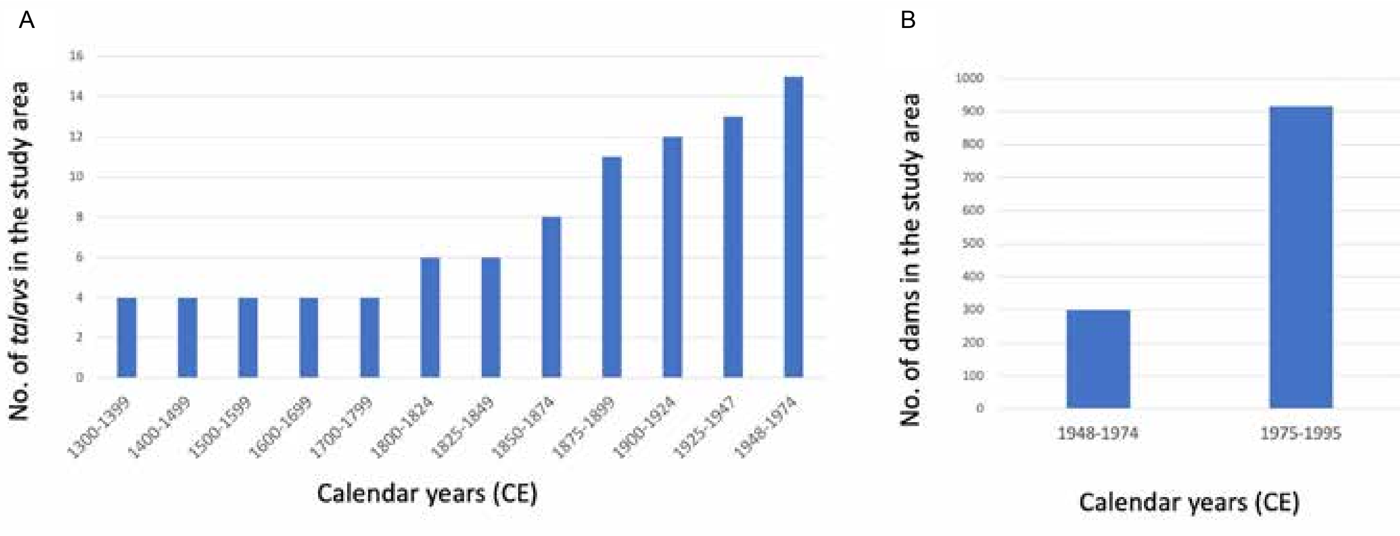


**Figure 2:** The proliferation of *talavs* in the study area. **(A)** Historical (1300–1974) proliferation of *talavs* in the study area. Source: Maharashtra State Gazetteers, India, gazetteers.maharashtra.gov.in. **(B)** Increase in the number of dams during the second half of the 20th century (1948–1995), most of which were constructed in the same way as the historical *talavs*. Source: Govt. of Maharashtra, India, maharashtra.gov.in.

of structure (e.g. age, height, composition, rate of maintenance of the dams). However, we find that it is the catchment-level manifestation of the large-scale Indian monsoon system that has the strongest impact on the erosional patterns preserved in the sediments of the *talavs*. Furthermore, we found that drier catchments in the Bhima watershed are at elevated risk of floods caused by anomalous heavy rainfall events in these catchments. Floods cause loss of top soil that is detrimental to farmers, who are the main stakeholders in the area.

**(b)** Analysis of information extracted from colonial administrative texts demonstrates that the *talavs* were first built in this region by the Mughals (~1500 CE) to provide water to local populations during dry spells. Later, the British colonialists, taking advantage of the fertile soil, developed this region intensively during the 18th–20th centuries as a cash crop agricultural center (first cotton, and then sugarcane). They did so by commissioning *talavs* (Fig. 2a) in response to famines (extreme food shortages associated with low rainfall; Ray et al. 2021) to serve two purposes, namely water conservation for agricultural purposes and to provide non-farm (alternate) sources of employment for local populations during famine years (Ray et al. 2021). After India gained independence in 1947, the government of India undertook a massive construction effort to build large (>15 m high) and small (<10 m high) dams to further increase water-intensive cash crop production (sugarcane) and generate hydroelectricity (Fig. 2b). The construction of *talavs* was key to preventing food shortages caused by rainfall variability in these semiarid regions and, eventually, turning the region into a major urban center and port.

**(c)** However, in-depth interviews with stakeholders conducted recently, especially with farmers, revealed that the presence of *talavs* has changed the nature of climate risks upstream and downstream of these water bodies. Farmers in the upstream region are more vulnerable to rainfall fluctuations than farmers in the downstream region, even though they are only 5 km apart. Downstream farmers continue to grow water-intensive crops like sugarcane and fruits (grapes, bananas), while upstream agriculture comprises less water-thirsty crops, such as millets. This differential access to water has resulted in unequal wealth distribution in the catchment area. In fact, newspaper reports suggest that in recent decades, hoarding of water in these *talavs* by powerful farmers may have escalated conflict and exacerbated existing inequalities, as demand for water has increased with growing reliance on water-intensive cash crops (Fig. 2b).

**Implications for policy and climate research**

*Talavs* provide catchment-level information on parameters such as the rate of loss of top soil, flood risk, etc. that are critical for informing policy and drawing management plans. Climate information preserved in sediments collected from the *talavs* also helps ground truthing downscaled climate models, critical for local climate prediction purposes. But most importantly, *talavs* provide invaluable insights into how human communities, based on their socioeconomic and cultural realities, respond to climatic changes. These insights address relevant climate–society questions such as human migration and conflict. Scientific exploration of small water bodies (Jacob et al. 2020; Penny et al. 2007) require multi-disciplinary and creative approaches, which can be logistically challenging and cost prohibitive to undertake. However, considering the value these explorations provide in understanding climate–society linkages, more studies should be undertaken. Finally, engaging with local populations, who use such resources to sustain their communities in a reciprocal manner, offers an opportunity for a more community-engaged approach to paleoscience.

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AFFILIATIONS

[1]CIRES and Center for Asian Studies, University of Colorado, Boulder, USA
[2]Indian Institute for Human Settlements (IIHS), Bengaluru, India
[3]Indraprastha Institute of Information Technology (IIIT), New Delhi, India
[4]Ohio State University, Newark, USA
[5]Indian Institute of Science Education and Research (IISER), Pune, India
[6]Indian Institute of Science Education and Research (IISER), Mohali, India
[7]State University of New York Maritime College, USA
[8]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences (MoES-IITM), Pune, India
[9]Pune University, India
[10]Deccan College-Deemed University, Pune, India
[11]University of British Columbia, Vancouver, Canada
[12]Indian Institute of Technology (IIT), Kharagpur, India

CONTACT

A. Bhattacharya: atreyee.bhattacharya@colorado.edu

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# Paleoenvironmental change and human activity at Okomu National Park, Nigeria

Emuobosa A. Orijemie[1], T.O. Ayelagbe[1], A.S. Diya[1], A.J. Ibirogba[2] and E.T. Olaleye[1]

**We studied palynological and archaeological proxies to reconstruct the environmental and human-ecological history of the Okomu National Park in Nigeria. We observed distinct environmental phases characterized by the interplay between mangroves, freshwater forests and human influence.**

Here, we show the results of some environmental archaeological investigations carried out in the rainforests of Okomu National Park (ONP), located 60 km northwest of Benin City in southern Nigeria. The ONP is a small area within the Okomu Forest Reserve (OFR); a forest block of about 1238 km$^2$ (White and Oates 1999; Fig. 1), and remains a fully protected park. Nowadays, the vegetation consists of Guinea-Congo lowland rainforest, including areas of mangrove swamp forest, freshwater swamp forest, high forest, secondary forest, and open scrub. Some of the most common trees are *Bombax buonopozense, Celtis zenkeri, Triplochiton scleroxylon, Antiaris africana, Pycnanthus angolensis* and *Alstonia congensis*.

Previous studies in the area (Jones 1955, 1956; White and Oates 1999) reported the occurrence of charcoal and pottery based on dugouts from several pits in compartments 43, 44, 65, and 86 in the park. According to the report, the pits showed three distinct layers. The deepest layer (100–50 cm) had only charcoal, the second layer (50–20 cm) had charcoal, charred palm kernels and pottery. The third and shallowest layer (20–0 cm) lacked any cultural, charred or microfossil remains, which was interpreted as an abandonment period. Based on these results, Jones (1956) and White and Oates (1999) stated that the landscape of the ONP was not always a rainforest, but must have been occupied by farmlands and villages in the past. Furthermore, charcoal samples collected from compartments 86 and 65 at depths of 20 cm and 28–20 cm yielded radiocarbon dates of 760 ±50 yr BP and 700 ±60 yr BP, respectively (White and Oates 1999). This indicated that ONP was abandoned about 760–700 years ago (12th–14th centuries CE) (White and Oates 1999). The question that arises is why these settlers left the area. The abandonment event has been attributed to at least three possible factors, namely (1) climate change; (2) epidemic; and/or (3) the war between the kingdom of Benin and Udo, a city-state on the northernmost part of the ONP (Jones 1956), which occurred during the late 13th century. However, these hypotheses remain untested. Therefore, this study was designed to reconstruct the environmental and human-occupation history of the ONP using palynological and archaeological data.

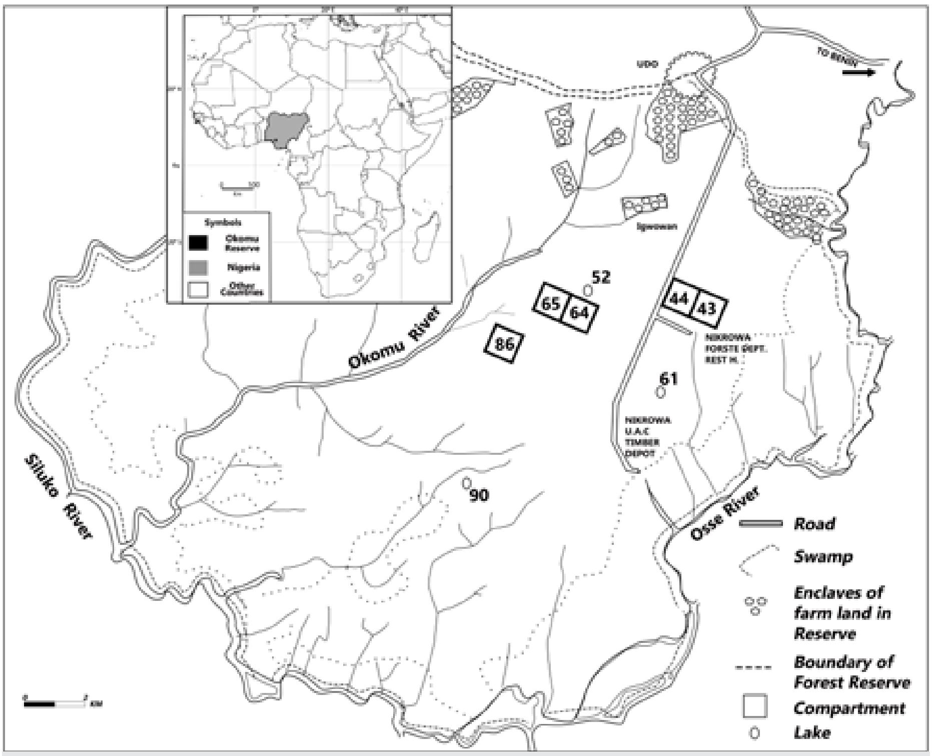


**Figure 1:** Map of Okomu National Park near Benin, southern Nigeria.

**Palynological and archaeological investigations**

For the palynological component, we collected sediment cores from Lakes 90, 61 and 52 in the ONP and analyzed the pollen, spores, diatoms and charcoal to reconstruct the park's environmental history. A one-meter square test pit (60 cm in depth) archaeological excavation was also conducted on compartment 65 to understand the occurrence and distribution of the cultural material in that part of the ONP.

The analyses of samples for palynological content yielded pollen grains, pteridophyte and fungal spores, algae and the lacustrine diatom *Aulacoseira* sp., which were used to distinguish three environmental phases; A, B and C (Fig. 2). For ease of interpretation, the pollen and spores were grouped into six ecological classes, namely mangrove swamp forest, coastal vegetation, freshwater swamp forest, freshwater, lowland rainforest and savanna. The earliest phase (A), was identified only in Lake 90 and was characterized by the presence of mangrove swamp forest, some secondary forest and freshwater taxa. By comparing this pollen assemblage with data from other sites in southern Nigeria and West Africa (Sowunmi 2004; Tossou et al. 2008), we interpreted that Phase A must have occurred between 3000 yr BP and 2000 yr BP. The intermediate phase (B), characterized by mangroves, freshwater and swamp forests taxa, and present in all the studied lakes, was interpreted as the first development of the rainforests. This development likely occurred between 1300 yr BP and 1200 yr BP (Orijemie 2020). We recovered pollen remains typical of anthropogenic disturbance of natural vegetation (*Asteraceae*), and economic plants (*Vernonia amygdalina, Zanthozylum* cf. *zanthoxyloides, Spondias mombin* and *Parkia biglobosa*) at a depth of 0.9–0.8 m in sediments of Lake 90 which corresponded to the terminal period of Phase B. These findings were interpreted as indicative of the presence of humans in Okomu. During the third phase (C), which was identified in all the lakes, there is a decline of the mangroves and secondary forest plants (*Elaeis guineensis* and *Alchornea* sp.), while rainforest taxa showed an increase. This vegetation change represents a marked decrease in human activities, and, hence, a regeneration of the rainforest at ca. 760–700 yrs BP.

 

The excavations in the test pit revealed three distinct stratigraphic layers. The deepest layer (60–40 cm) was devoid of artefacts, although we found a relatively high amount of charcoal particles. The occurrence of charcoal could either be of anthropogenic or natural origin. The remains of potsherds, charred palm kernels (*Elaeis guineensis*) and the cranial bone of catfish (*Clarias* sp.) in the second layer (40–20 cm) suggest the presence of settlers who carried out some agricultural and fishing activities. The third stratigraphic layer (20–0 cm) did not have any palynological or archaeological remains. This last sediment horizon probably represents the period when the Okomu area was abandoned, allowing the forest to regenerate.

**Human occupation of Okomu National Park**

The archaeological data suggest the presence of humans in the ONP at least between the 12th and 14th centuries CE, which agrees with previous findings by Jones (1956), and White and Oates (1999) about human occupation in this area. Palynological evidence from the region also supports this chronology, as sediment cores from Okomu Lakes 90, 61 and 52 showed human presence at depth 90–80 cm of Lake 90, 50–0 cm of Lake 61, and 45–0 cm of Lake 52 sediment cores. This is the first time that pollen indicators of human disturbance and economic plants are documented in the ONP. Furthermore, the distribution of archaeological materials across a large area, stretching over 15 km, also provides unique evidence that the ONP was a "densely populated and intensively cultivated landscape" (White and Oates 1999) before the final abandonment during, or shortly after, the 14th century CE.

**The Okomu abandonment event**

As indicated earlier, the abandonment event has been attributed to at least three possible factors, namely (1) climate change; (2) epidemic; and/or (3) the war between Benin and Udo. There are reports of the occurrence of a dry climate in West Africa during the 14th–16th centuries CE (Lézine et al. 2019; Logan and Stahl 2017) that had significant demographic impact in the region. However, this dry phase has not been identified in palynological records from the Okomu sediment cores, which showed an increase in rainforest taxa during that time. The outbreak of an epidemic has been documented in the location of Iguowan, within the ONP, but 200–150 yrs ago (Jones 1956), after the abandonment of the Okomu region. Udo rivalled Benin for centuries, but it was destroyed twice by the forces of the ruler of Benin (called Oba); first by Oba Oguola at around 1285 CE (Egharevba 1960), and second by Oba Esigie at ca. 1520 CE (Jones 1956). The warfare in ca. 1285 CE would be contemporaneous with the period when the Okomu area was abandoned, and when the rainforest regenerated and became floristically diverse, as noted in the pollen record.

This work investigated the environmental and human-environment history of the Okomu National Park. We showed, using a combination of palynological evidence and archaeological data from diverse types of sediment records in the Okomu forest, that there were landscape changes due to a combination of natural and anthropogenic factors. More importantly, we observed clear evidence that the area was inhabited until the 14th century CE when it was abandoned, most likely because of the warfare between the kingdoms of Benin and Udo.

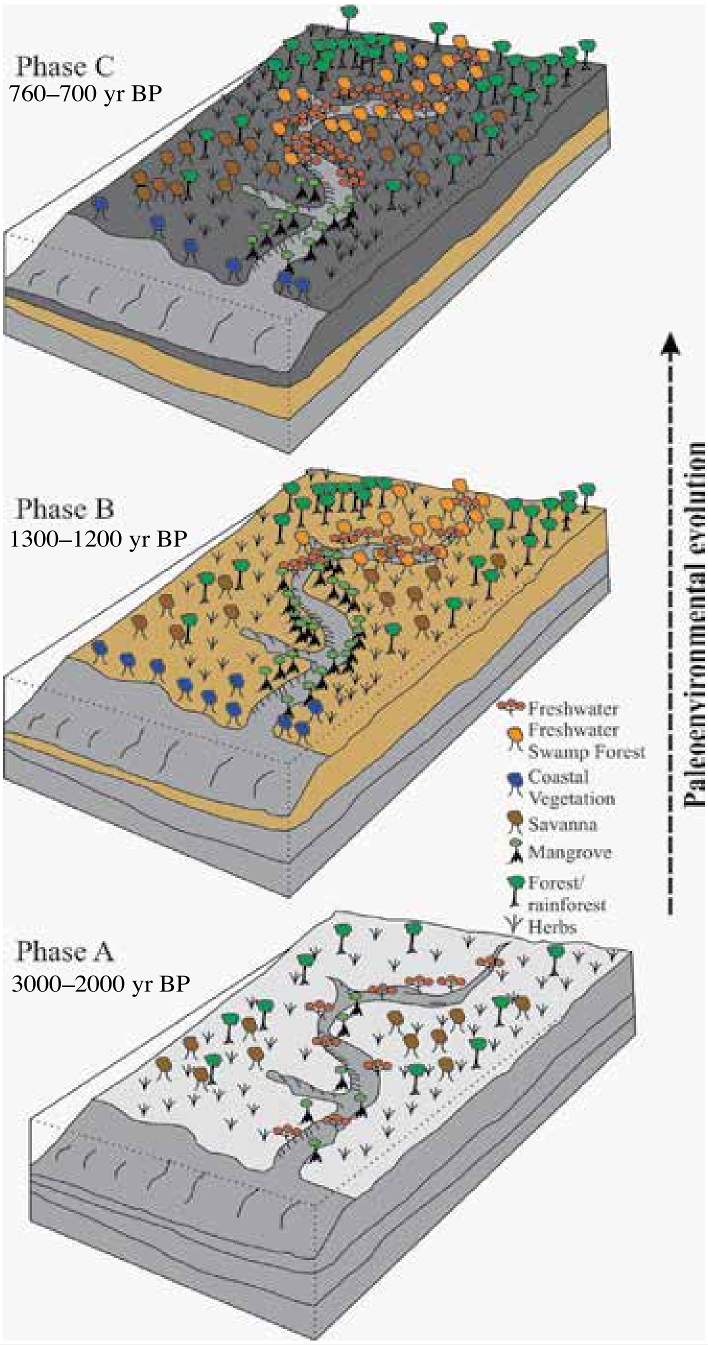


**Figure 2:** The reconstructed environmental changes in the Okomu National Park, Nigeria.

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AFFILIATIONS

[1]Department of Archaeology and Anthropology, University of Ibadan, Nigeria

[2]Department of Earth and Environmental Sciences, Columbia University, New York, USA

CONTACT

Emuobosa A. Orijemie: orijemie17@gmail.com

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# Newly discovered Plio-Pleistocene sites in west Mt. Kenya: Potential tropical high-elevation refugia?

Rahab N. Kinyanjui[1,2,3], A. Grossman[4], F. M. Kirera[5,2], V. Waweru[6,2], N.R. Malit[7,2], C. Omuombo[8,2] and CHK research team*

**The Central Highlands of Kenya (CHK) sites offer a unique opportunity to investigate evolutionary history during the Plio-Pleistocene period. Preliminary data indicate stable vegetation cover with continued hominin occupation of the sites, especially during extreme climates.**

East Africa is renowned for its rich fossil and artefact record, especially on human evolutionary history, technological innovations, and advancement. Most East African prehistoric sites are found within, or in close association with, the East African Rift System (EARS). Here, we report on new fossil locality from the CHK that are unassociated with the EARS (Kirera et al. 2001; Malit et al. 2003). It is located at high elevation and surrounded by Mt. Kenya, the Aberdare Range, and the Mathews Range (Fig. 1). The mountain ranges influence local precipitation which differs from the country's bimodal rainfall pattern (Nicholson 2017).

The CHK sites were discovered in 1999. Key fossil findings include remains of extinct megafauna; a fossilized tooth (lower p4) of a pig (*Nyanzachoerus* sp.); two kinds of extinct elephant (*Deinotherium* sp. and *Anancus* sp.); giant, long-horned wild cattle (*Palerovis* sp.); Carnivora; wild horses; small antelopes; and archaic *Homo sapiens* (Kirera et al. 2001; Malit et al. 2003). In addition, lithic technologies ranging from Early- to Late- Stone Age were also discovered. Based on the fossil evidence and the toolkits present, sites at the CHK span the last 5 Myr and may provide important information about a major extinction of African megafauna recorded at ca. 4.6 Myr BP (Faith et al. 2018).

To date, around 15 fossil-bearing sites have been identified at the CHK, providing a record that spans the earliest Pliocene through to the Holocene. Based on this fossil evidence and the transitional lithic technologies present, we conclude that the history of occupation at the sites is long, suggesting that CHK has been continuously resourceful and accessible to both fauna and humans for the Plio-Pleistocene (Kirera et al. 2001; Waweru, personal communication). Hence, CHK was occupied through periods of extreme climate variability recorded during the Pleistocene (Kaboth-Bahr et al. 2021). These attributes make CHK unique compared to other sites associated with the EARS, which more often represent intermittent occupation.

During the Plio-Pleistocene, as well as today, the CHK ecosystem was characterized by a habitat mosaic. The main goal of studying the past vegetation at the CHK is to understand the role played by the high-elevation sites of the CHK in the evolution of hominins and associated fauna and flora in East Africa during the Plio-Pleistocene. Specifically, this paper addresses the question of environmental dynamics attributed to variable wet-dry climates using palynological data.

### Geological, paleontological and archaeological settings

CHK sites are located at high elevation associated with complex geological activities of the uplift and volcanism linked to the formation of Mt. Kenya to the east and

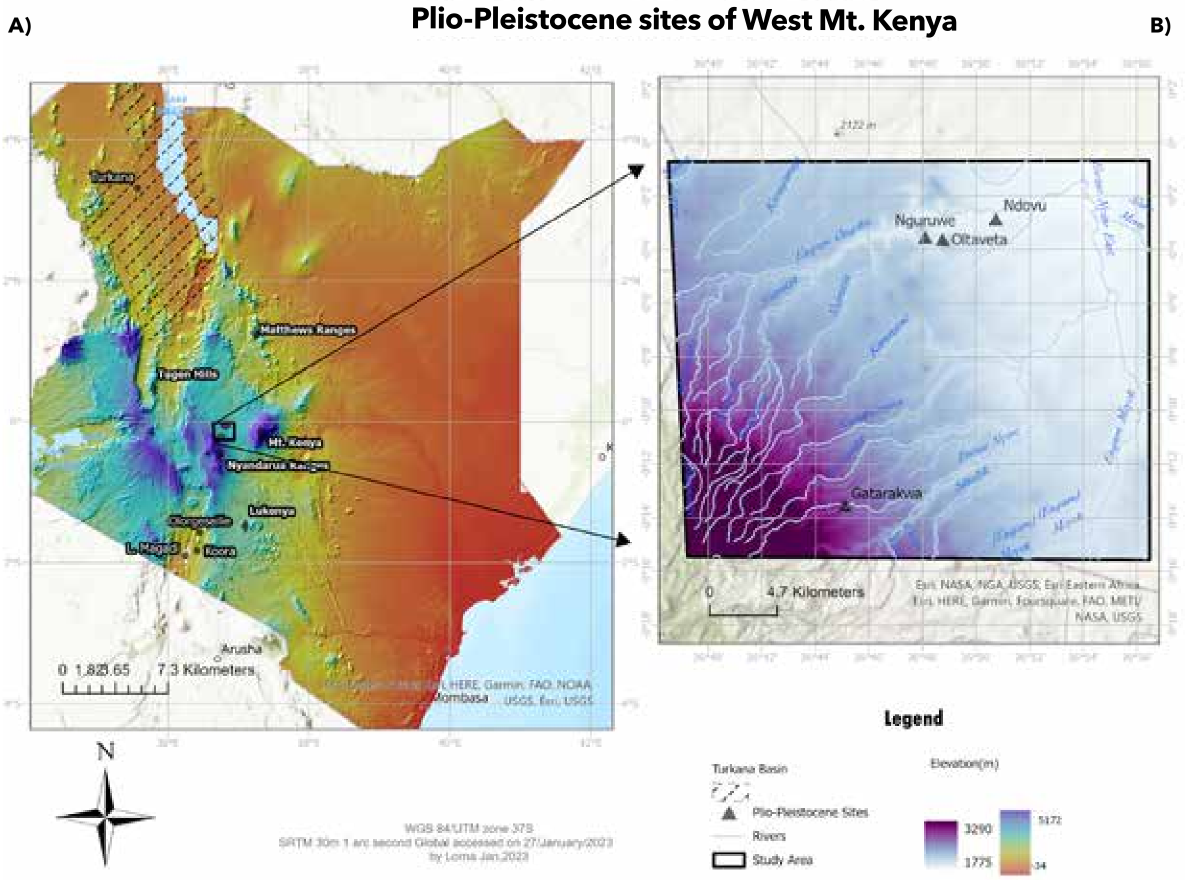


**Figure 1: (A)** Map of Kenya showing the Central Highland Kenya (CHK) locality, mountain ranges, and other comparable sites associated with the East Africa Rift System (Turkana Basin, Tugen Hills, Lukenya). **(B)** Map showing location of different CHK sites.

 

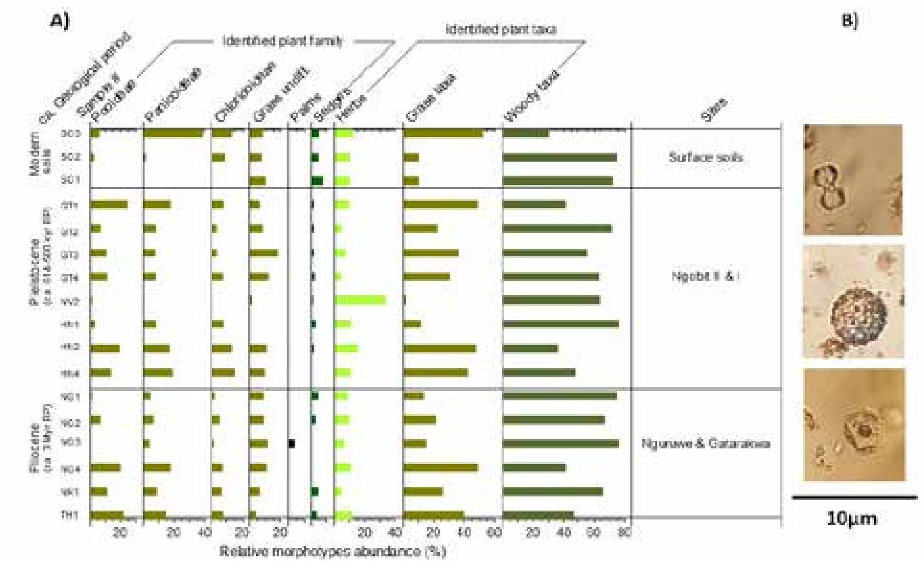


**Figure 2: (A)** Diagram showing relative morphotypes abundance and identified plant families using fossil phytoliths analyzed from CHK sites. Vertical axis shows the geological period brackets of the sites and the samples analyzed. The horizontal axis shows relative morphotypes abundance and the identified plants/taxa in different samples. **(B)** Microphotographs of some of the phytoliths identified (from top to bottom): bilobate from grass, globular ornate from woody taxa, and achene from sedges.

the Aberdare Range to the west (Fig. 1). Radiometric dating ($^{40}Ar/^{39}Ar$) of volcanic tuffs from the CHK yielded ages of ca. 3 Myr BP, while biostratigraphic correlation indicates an age of ca. 5 Myr BP. Faunal fossils at the Nguruwe site include extinct pig *Nyanzachoerus* cf. *kanamensis*, which has been recorded in Pliocene sediments in the Turkana Basin and Tugen Hills (Bishop 2010; Hill et al. 1986). Remains of the extinct bovids *Megalotragus* spp. and *Damaliscus* spp. are also found at Ngobit and Oltaveta sites, and were previously recorded in Pleistocene deposits at the Lukenya sites (Faith et al. 2012; Potts and Deino 1995). Ngobit sites also preserve lithic technologies from Early-to Late Stone Age. One of the sediment layers at Ngobit was radiometrically dated, yielding ages between 614 kyr BP and 500 kyr BP, and containing hominin skull fragments, as well as Acheulean and transitional Acheulean to Middle Stone Age tools (Waweru, personal communication).

### Site significance

Highlands, among other zones such as coastal forests, lake margins and riparian habitats, are identified as potential tropical Quaternary refugia (Basell 2008; Joordens et al. 2019; Lahr and Foley 2016). Paleontological and archaeological evidence suggest that CHK sites were most likely refugia sites, being resourceful and habitable especially in events of extreme aridity in the East African region (Faith et al. 2012; Maslin et al. 2014). As the tropical African climate periodically shifted between humid and dry conditions, the CHK provided favorable and preferred habitats through orographic lift and topographic attenuation of orbitally forced climatic changes (Maslin et al. 2014). We hypothesize that the CHK biomes were resilient to remote climatic forces and, therefore, continuously habitable from the Pliocene to the Holocene period.

### Vegetation data

This paper presents preliminary vegetation data inferred from phytolith analyses at several CHK sites. Phytoliths are silica plant cells' casts formed in plants during growth. Upon plant decomposition, the cell casts are deposited in the soils and stay preserved for long periods of time. Their unique morphological features enable identification and classification of plant families (sedges, palms, and grasses) and taxa (woody, grasses, and herbaceous) (Piperno 2006). Phytoliths are reliable proxies to distinguish between C3 and C4 grasses, offering critical information on past temperature and precipitation (Fredlund and Tieszen 1997). C3 grasses are adapted to cool climates in tropical highlands, while in temperate regions they are even found at low elevations. C4 grasses constitute the highest proportion of low-elevation vegetation cover, with C4 tall grasses thriving best in warm and humid climates, while C4 short grasses are adapted to hot and dry climates (Piperno 2006). We processed and analyzed 20 samples collected from Pliocene and Pleistocene CHK sites to investigate if vegetation cover and structure differed between the two geological periods. We compared the vegetation data with the available faunal data to examine if both datasets reflect similar paleoenvironmental conditions at CHK

### Significance of the vegetation data

Figure 2a shows the relative proportion of plants identified to family level (grasses, palms, and sedges) and taxa level (herbs, grasses, and woody taxa) using fossil phytolith, while Figure 2b are examples of the morphotypes identified. Phytolith data from the fossil samples reflect mixed wooded grasslands consisting of C3 and C4 grasses at CHK during the Pliocene and Pleistocene. However, the proportion of woody versus grass taxa varies across samples within the same age range. Some samples have a significant proportion of sedge and palm phytoliths, indicating that wetland habitats were dominant at CHK. Phytolith data from the modern soil samples (Fig. 2a) indicate mixed wooded grasslands, but with proportions varying across samples. This suggests vegetation cover has been stable and consistent on the CHK landscape since the Pliocene period. CHK sites, therefore, have been a suitable habitat for a variety of faunal species, including hominins.

While paleontological data at CHK sites indicates strong evidence of a megafaunal extinction at the Pliocene-Pleistocene boundary, stability of vegetation data shown here indicates that it is unlikely that changes in vegetation contributed to that extinction. Instead, the stable composition of the paleovegetation likely contributed to act as refugia hotspots which supported species survival long before the extinction. Ongoing research at the CHK is trying to refute this hypothesis. Paleoenvironmental information in the East African highland sites is currently lacking, or scarce. Therefore, more research is necessary to provide crucial information on faunal evolution history in this region.

AFFILIATIONS

[1]Department of Archaeology, Max Planck Institute of Geoanthropology, Jena, Germany
[2]Department of Earth Sciences, National Museums of Kenya, Nairobi, Kenya
[3]Human Origins Program, Smithsonian National Museum of Natural History, Washington, USA
[4]Department of Anatomy, College of Graduate Studies, Midwestern University, Glendale, USA
[5]Department of Biomedical Sciences, Mercer University, Macon, USA
[6]Council on African Studies at the MacMillan Center for International and Area Studies, Yale University, USA
[7]Department of Anthropology, SUNY, Potsdam, USA
[8]Department of Geosciences and the Environment, Technical University of Kenya, Nairobi, Kenya
*See the online version for the complete author list

CONTACT

Rahab N. Kinyanjui: kinyanjui@shh.mpg.de

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# Insight into the 4.2 ka event records in northeast India: A global connection and the geological evidence

Nivedita Mehrotra and Santosh K. Shah

**The local response of the environment to climate forcing in northeast India during the 4.2 ka event was coupled with human response to global changes in the natural environments. These sudden changes were coincidental to the decreased southwest monsoon strengths.**

### The 4.2 ka event

The response of the natural environment towards extreme climate events also has consequences for human societies. Abrupt climate change events, such as the 4.2 ka event, led to the global demise of several once-developed and flourishing human civilizations. In the eastern Himalayas, this was correlated with prolonged multi-decadal to multi-century droughts (Mehrotra et al. 2019).

There could have been natural forcing factors behind this sudden demise of populations observed in the Indus valley of ancient India, Egypt, and Mesopotamia around 4 kyr BP (Mehrotra et al. 2019). The forcing factors that led to this abrupt climate change event, coupled with human response, were sudden change in the monsoon pattern, fluctuation in solar radiation, and reduction in the sea-surface temperature (Berkelhammer et al. 2012; Bond et al. 2001; Dixit et al. 2014 and references therein; Hong et al. 2003; MacDonald 2011; Staubwasser et al. 2003).

Proxy records of paleoclimatic change during the 4.2 ka event have been studied at a global scale (Mehrotra et al. 2019). A few multi-proxy records in high-altitude settings in northeast India also record marked cold and dry conditions, such as at the Ziro and Pankang Teng Tso (PTTso) lakes in the eastern Himalayas (Ghosh et al. 2014; Mehrotra et al. 2019), or at Darjeeling Himalaya (mountain range in the foothills of the eastern Himalayas) (Gosh et al. 2015). In other locations, such as Lower Subansari and Assam, a reduction in monsoon strength was observed during the same period (Fig. 1) (Bera and Basumatary 2013; Tripathi et al. 2019).

### Fluvial and lacustrine sediment records

The climate fluctuations during the mid-Holocene, and prevailing cold-dry conditions around 4.2 kyr BP, were observed in palynological, carbon isotope and paleomagnetic records from sediments at the catchment of PTTso Lake (Mehrotra et al. 2019) (Fig. 1: Site 1). The palynological and carbon isotope evidence from the sediments of the Neora and Murti river beds in the Jalpaiguri district of Darjeeling Himalaya (Fig. 1: Site 2) indicate a weak monsoon during ca. 4.3 to 3.5 kyr BP, impacting the regional plant community (Ghosh et al. 2015). The paleoclimatic interpretation of the pollen and carbon isotope records of Ziro lake record in Arunachal Pradesh, eastern Himalayas (Fig. 1: Site 3) was also similar (Ghosh et al. 2014).

The mean annual air temperature in this region of the eastern Himalaya increased, and the strength of the southwest monsoon has decreased since 3.8 kyr BP, thereby causing a reduction in forest cover (Ghosh et al. 2014). The study site at the lower Subansari region of Assam, in northeastern India, records a reduction in monsoon strength

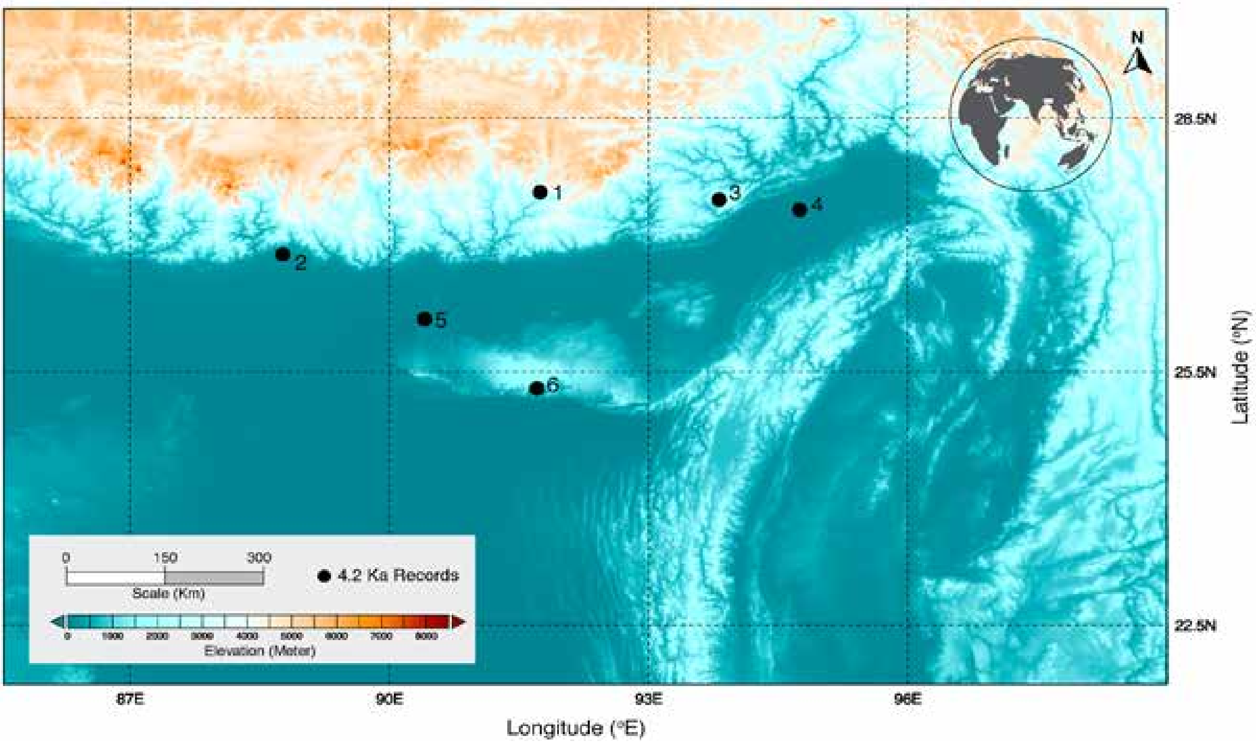


**Figure 1:** Map showing the sites (black dots) in northeast India in which the 4.2 ka event has been identified based on palynological, paleomagnetic and carbon isotope evidence. (1) PTTso Lake (Mehrotra et al. 2019), (2) Neora and Murti river beds, Darjeeling Himalaya (Ghosh et al. 2015), (3) Ziro lake (Ghosh et al. 2014), (4) lower Subansari (Bera and Basumatarey 2013), and (5) Deepor wetlands of Assam (Tripathi et al. 2019). Site (6) is the location of the entrance to the Mawmluh Cave, Meghalaya, and the locality of the speleothem type specimen for the GSSP for the Meghalayan Stage and Upper Holocene subseries.

 

**Figure 2:** Speleothem KM-A from the Mawmluh Cave, Meghalaya, the type specimen of the Meghalyan Stage and Upper Holocene subseries (image credit: Museum BSIP, Lucknow).

(Fig. 1: Site 4). Paleovegetation reconstructions, based on palynological analysis of subsurface sediments from trenches of exposed fluvial deposits, suggest prevailing warm and dry conditions at around 4.3 kyr BP (Bera and Basumatary 2013).

Other pollen records from the Deepor wetlands of the western Bhramaputra flood plains in the tropical parts of Assam (Fig. 1: Site 5) also indicate less humid conditions, and a decline in southwest monsoon strength (Tripathi et al. 2019). This site records variations in forest cover, such as reduction of the Sal forests constituents (*Shorea robusta* and *Terminalia* sp.), along with the loss of marshy elements around 4.6 kyr BP, which was followed by a decline in tree taxa between 3.4 and 2.2 kyr BP (Tripathi et al. 2019).

While being cautious about potential chronological uncertainties between those studies, we can conclude that collective proxy evidence indicates that an arid phase began at around 4.2 kyr BP in the northeast part of India, which was characterized by a rise in air temperature, and weakening of the southwest monsoon. However, the manifestation of this trend in air temperature and precipitation was not accompanied by indications of human migrations, or any social impact in this region.

## Speleothem records

The Cherrapunji region of Meghalaya in northeast India records one of the country's highest annual rainfalls, due to the seasonal influences of the monsoon. Speleothems from Mawmluh Cave in Meghalaya (Fig. 1: Site 6) are excellent archives of the monsoonal dynamics of the past. This site lends its name to the latest geological stage of the Quaternary, the Meghalayan Stage, which was formally ratified by the International Commission on Stratigraphy in June 2018 (Head 2019).

The lower boundary of the Meghalayan Stage begins at 4250 yrs before 2000 CE (Head 2019). The stalagmite retrieved from Mawmluh Cave (Fig. 2) is also the Global Boundary Stratotype Section and Point (GSSP). The $\delta^{18}O$ data from this U/Th dated speleothem shows an abrupt climatic change at the 4.2 ka event, which has become a benchmark for the study of climate impact on human civilizations across Europe and Asia.

The 4.2 ka event forms the basis of the Meghalayan Stage/Age and the coincident subseries/subepoch of the Late/Upper Holocene (Walker et al. 2018). The Birbal Sahni Institute of Palaeosciences in Lucknow, India, conserves the type specimen of the Meghalyan Stage and the speleothem KM-A from Mawmluh Cave in Meghalaya (Fig. 2).

## Holocene event and its cultural response to civilization

Coupled human and environmental response of this so-called 4.2 ka abrupt climate change event are often observed in proxy records distributed globally. The northeast India region was subject to human migration towards eastern Asia during the Late Holocene (Tagore et al. 2022). This region is also known as a biodiversity hotspot, and a flora and fauna migration corridor to the subcontinent. In contrast to other regions in which there are archaeological studies available in different parts of the Middle East (Mehrotra et al. 2019), in northeast India there is a distinct lack of archaeological evidence that prevents the study of human response to the 4.2 ka event in this region, and to link it to a global civilization collapse event. Nevertheless, the recognition of the Mawmluh Cave site as a geological heritage site by the International Union of Geological Sciences, due to its key relevance for the understanding of the impact of climate change on human civilizations, proves the significance of northeast India as a recorder of the 4.2 ka event. The preservation of abrupt climatic change event signals is evident in other paleoclimatic records from northeast India (Mehrotra et al. 2019), including isotopic, palynological and sedimentological proxies. Additional and more exhaustive work is needed to find supportive evidence of human-induced changes, or coupled societal implications, during the 4.2 ka event in this region.

AFFILIATION

Birbal Sahni Institute of Palaeosciences, Lucknow, India

CONTACT

Nivedita Mehrotra: nivedita_mehrotra@bsip.res.in

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# pSESYNTH project: Community mobilization for a multi-disciplinary paleo database of the Global South

Charuta Kulkarni[1], I.A. Jara[2], M. Chevalier[3], X. Benito[4] and pSESYNTH participants*

**How to enhance paleoscientific research, collaboration and application in the Global South? The INQUA-funded multi-year pSESYNTH project envisions the first multi-disciplinary Holocene paleo database through a collaborative vision for past human–environmental systems in the Global South, and their future sustainability.**

The value of, and theoretical basis for, interdisciplinary approaches in paleosciences has been widely recognized (e.g. Dearing et al. 2011; Fischer et al. 2021). Meanwhile, it has also been realized that identifying feasible and inclusive strategies to put interdisciplinarity into practice requires continued community mobilization and collaboration (Swanson et al. 2021). Here, we bring an example of scientific community mobilization and collaboration focused on the Global South; the geographical region covering Latin America and the Caribbean, Africa, Asia, and parts of Oceania (Fig. 1), where researchers have been historically, and often continue to be, marginalized from international collaborations (Maas et al. 2021).

The study of past global changes and their interactions with socio-environmental systems is highly underrepresented in the Global South. Yet, its diverse landscapes, including tropical forests, high-latitude alpine areas and grasslands, coastal wetlands, as well as polar regions under climatic and anthropogenic pressures, urge for an unbiased understanding of human–environmental dynamics at different spatial and temporal scales.

Moreover, most, if not all, developing countries are part of the Global South, bringing an additional challenge in relation to ecosystem conservation, management, and exploitation of natural resources (Lebel and McLean 2018; Monsarrat and Svening 2021; Raja et al. 2022). Given the long histories of human occupation and the influence of past climates and land-use practices in shaping landscapes of the Global South, understanding the interactions among climate, human societies, and ecosystems is key to improving the knowledge of pressing environmental challenges.

**pSESYNTH: genesis and objectives**
Stemming from the PAGES-INQUA supported early-career researcher workshop on "Past Socio-Environmental Systems (PASES)" (pastglobalchanges.org/calendar/26972) in 2020, the INQUA-funded project "The whole is not the sum of the parts: building a synthesis database of past human-environmental systems in the Global South (pSESYNTH)" has initiated research collaborations among paleoscientists from, and/or working on, the Global South and other underrepresented regions of the world (e.g. Australia, Southeast Europe).

Pursuing the Integrated, Coordinated, Open, and Networked (ICON) approach (Koren et al. 2022), the overarching goal of pSESYNTH is to establish, articulate and strengthen regional, interdisciplinary teams for studying past socio-environmental systems of the Global South, and to build the first multi-disciplinary paleo database representing its regions.

pSESYNTH primarily focuses on the Holocene (the last 11.7 kyr) because: (i) there is greater spatial availability and better chronological controls of the datasets compared to the Pleistocene, and (ii) the Holocene is characterized by a progressive degree of anthropogenic influence over landscapes, offering ways to explore the evolution of diverse socio-environmental systems. Under the pSESYNTH framework, linking proxies of environmental change with climatic signals and societal processes (e.g. subsistence strategies, growth rates, migrations) will provide baselines to pose and test multiple hypotheses for explaining the trajectories of socio-environmental systems. Specifically, pSESYNTH activities are being developed around three main objectives (Fig. 2):

1) To **explore** drivers of past environmental change combining a diverse set of proxy information, organized into three themes: paleoecology (e.g. pollen, charcoal, diatoms), paleoclimatology (e.g. biomarkers, stable isotopes, varves, numerical simulations), and archaeology (e.g. radiocarbon dates, phytoliths, archaeobotanical remains, material culture).

2) To **quantitatively analyze** the links among paleoecology, paleoclimatology and archaeology, with an emphasis on research questions that can be generic across the Global South (e.g. are there connections, or commonalities, between colonial legacies and the evolution of socio-environmental systems in the Global South?) or specific to each subregion (e.g. at what spatial and temporal scales were human-environmental systems coupled or uncoupled to climatic fluctuations?).

3) To **share** the outputs and products of the project in the form of a database that meets the FAIR (Findable, Accessible, Interoperable and Reusable) principles (Wilkinson et al. 2016). pSESYNTH participants will capitalize on existing single- and multi-themed databases (e.g. Neotoma, NOAA, PANGAEA, p3k14c, ArchaeoGlobe) in complementing their data contributions in the novel Global South database. Together, the FAIR–ICON principles will underpin the database organization and will ensure geographic coverage, comparability, and accessibility for time-series data synthesis, which is crucial for mainstreaming paleoscience research from the Global South.

**Paleoscientific synthesis: Early insights**
Drawing upon the newly built Global South network (Fig. 1), the pSESYNTH project has been facilitating discussions on how varied datasets from different Global South regions can be effectively consolidated, and to achieve this goal, how critical it is to continue strengthening dialogues across

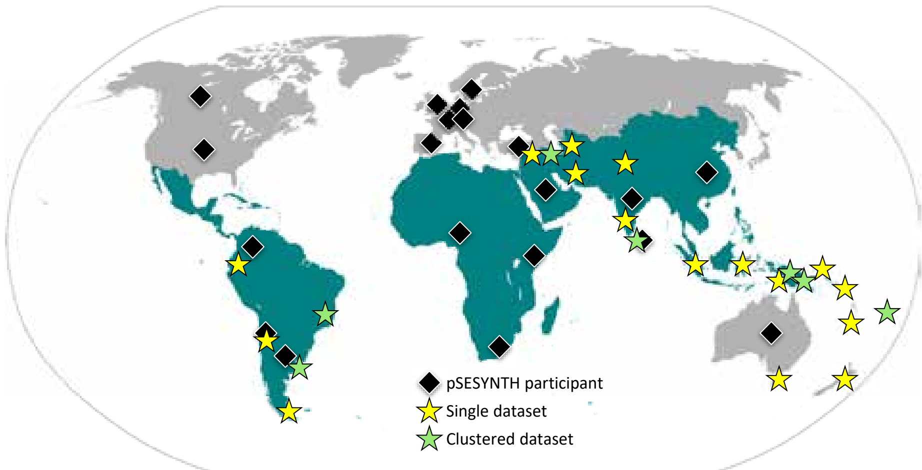


**Figure 1:** Map showing the regions of the Global South (in green), which is the geographical focus of pSESYNTH. Black diamonds show distribution of pSESYNTH participants from and/or working on the Global South. Yellow and green stars show the location and nature (single or clustered) of the datasets gathered so far.

pSESYNTH: A Multi-Themed Paleo Database for the Global South

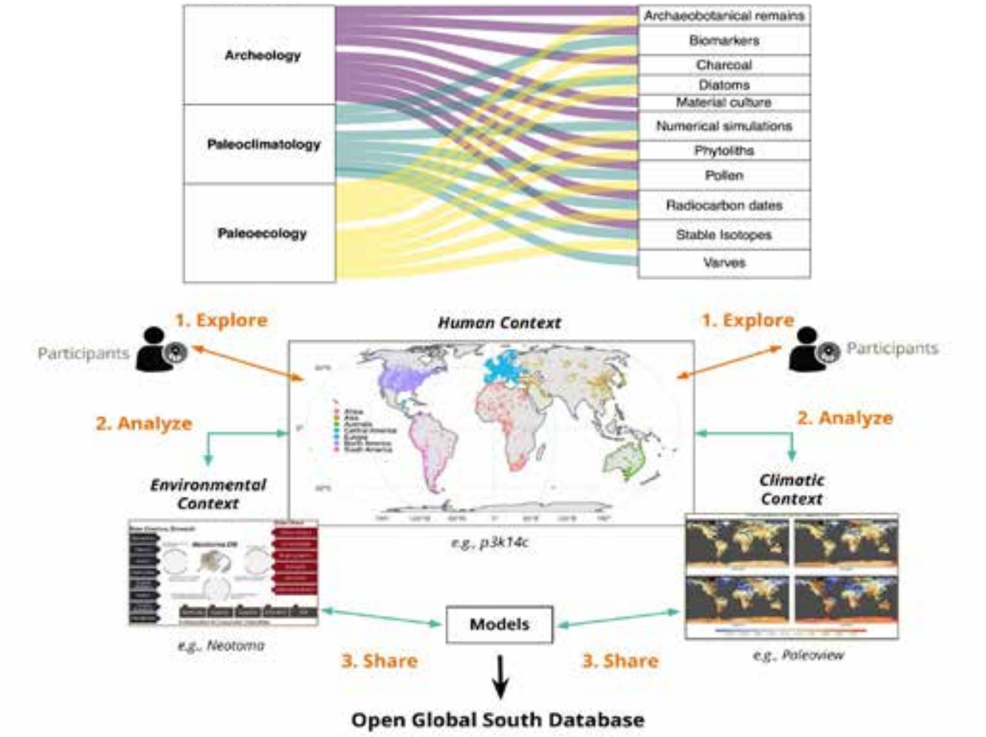


**Figure 2:** Schematic diagram showing pSESYNTH's objectives (explore, analyze, and share) and the core themes (paleoecology, paleoclimatology, and archaeology) under exploration, driving the synthesis of ideas, as well as datasets, provided by the project's participants and published databases.

the sub-disciplines of paleoscience. To this end, pSESYNTH has encouraged hands-on opportunities for developing three region-specific subgroups – the Americas, Asia-Africa, and Australasia-Oceania – that have been stimulating community-led research questions and syntheses of datasets at the intersection of climate, humans, and environment.

While there are multiple lines of inquiry (e.g. fire history, food production, extreme events, island colonization) that appeal to the respective subgroups, the topic of collective interest across the Global South is spotting changes in land-use patterns under pre- and post-colonial contexts. For example, in the case of the Americas, a preliminary exploration of pollen sites in the Neotoma database yielded 18 records, out of which 15 sites contain non-native pollen taxa such as *Rumex* and *Plantago* from 500 cal yr BP onwards, suggesting rapid and widespread European influence on the landscapes.

In the current pSESYNTH database, eight datasets contain lake sediment records from the Americas, yet they represent a small proportion of the >1300 cores available in the Latin American Pollen Database (latinamericapollendb.com) to unravel the complexities of colonization processes in the subregion (Flantua et al. 2015). Similarly, questions of when and how colonization altered island ecosystems has also been the focus of the data synthesis for the Australasia-Oceania subregion, where most of the database entries are high-resolution lacustrine pollen records. These records can be used to develop hypotheses on the role of colonial legacies in the evolution of socio-environmental systems in the Global South (e.g. Burney 1997).

Unlike the other two, the Asia-Africa subregion is visibly the most paleodata-poor subregion of the Global South (Fig. 1), currently lacking the spatial coverage and temporal resolution in identifying the impacts of colonialism. The available paleorecords from the Asia-Africa subregion, however, can help discern region-specific, perhaps continental scale, patterns for long-term vegetation change, land use, and landscape management, thereby complementing knowledge emerging from other subregions of the Global South.

Through as many as 64 records are integrated in the pSESYNTH database so far, the topics of common interest within and across the subregions find direct links to identifying historical baselines to constrain scenarios toward practical strategies for sustainable management of the Global South landscapes.

**Future directions**

The prime goal of pSESYNTH is to design a functional database structure, containing curated sets of interdisciplinary case studies from the Global South, aimed at providing reference data to foster collaborations among paleoscientists. The database produced as the final outcome of pSESYNTH will be publicly available online, and accessible via R shinyApp (Chang et al. 2022), which will work as a platform for visualizing the datasets, as well as for locating complementary datasets from other databases.

Raw data assigned with DOIs will be securely stored in a repository (e.g. Zenodo), ensuring ownership credits to the original contributors along with secured and transparent data reusability guidelines before the final products are released. In the upcoming years, pSESYNTH activities will continue to cross-fertilize knowledge and methods, utilizing the INQUA HABCOM support and upcoming PAGES-INQUA synergistic activities as platforms, all oriented towards enhancing paleoscientific research, collaboration and application in the Global South.

AFFILIATIONS
[1]Independent researcher, Chennai, India
[2]Departamento de Ciencias Históricas y Geográficas, Universidad de Tarapacá, Arica, Chile
[3]Institute of Geosciences, Section of Meteorology, Rheinische Friedrich-Wilhelms-Universität, Bonn, Germany
[4]Marine and Continental Waters Programme, Institute of Agrifood Technology and Research, IRTA, La Ràpita, Spain
*See the online version for the complete author list

CONTACT
Charuta Kulkarni: ckulkarni@gradcenter.cuny.edu

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# Interrogating the digital eye: Building capacity to analyze and interpret sedimentary charcoal records from African grassy biomes

Abraham N. Dabengwa[1,2], E. Twala[1], M. Govender[2], J. Finch[3], S. Archibald[2] and M. Bamford[1]

**PAGES Inter-Africa Mobility Research Fellow, Dr. Abraham Dabengwa, was hosted by Dr. Jemma Finch for one week at the University of KwaZulu-Natal, South Africa. From 29 August–2 September 2022, he explored digital analysis of sedimentary charcoal, discussed challenges around African paleofire research, and broadened his scientific network.**

Fire is a global driver of vegetation dynamics and biodiversity, and a key regulator of terrestrial carbon stocks. Forested biomes storing extensive aboveground carbon reserves are threatened by increasing fire activity from global warming and rainfall deficits (Pechony and Shindell 2010). Meanwhile, in tropical savanna and grassland biomes (i.e., tropical grassy biomes) where fire is considered endemic (Dabengwa et al. 2022), evidence shows declining fire activity. Ironically, global climate and biodiversity management policies still treat biomes with trees indiscriminately, often ignoring diverse fire histories. Publicly available global fire data is mainly derived from airborne imaging sensors developed in the last 70–80 years. However, this short timescale limits analysis of nuanced social, ecological, and climate changes shaping grassy biomes. This is where the quantification of charcoal fragments from sedimentary deposits could extend temporal fire reconstructions.

Charcoal fragments from depositional environments give clues about past fire behavior and patterns. For example, charcoal amounts are used to infer burned area, fire prevalence, and fire intensity (Duffin et al. 2008); charcoal-size abundance distributions indicate fuel flammability gradients and transitions among alternative vegetation states (Dabengwa et al. 2022); and charcoal shape factors represent fuel characteristics (Umbanhowar and McGrath 1998). Digital image analysis has advanced the analysis of shape factors linked to coarse-woody versus fine-grassy fuels (Aleman et al. 2013), with data produced at high spatial and temporal resolution. Shape factors including elongation ratios have been studied for charcoal produced by various plants (Umbanhowar and McGrath 1998). However, shape factors are considered unchanged from charcoal production to accumulation in sediments, and after sample processing.


**Figure 1:** Supervised analysis of charcoal using edge-detection from CharTool v1 macro in ImageJ. Users select a charcoal fragment, then the algorithm draws an outline around the fragment and calculates measurements (Image credit: Enele Twala).

To test the assumption of stationary shape factors in fuel attribution, we compared samples from African grassy biomes with frequent fire, fragmented fuel-beds, local presence of woody graminoids like reeds, and trampling by large herbivores. We had the following objectives:

- Design a study to conduct reproducible sedimentary charcoal image analysis;
- Build local capacity in charcoal image analysis by training junior research assistants; and
- Test the sensitivity of charcoal shape factors at sites with contrasting fire and grazing disturbance histories, sample preparation methods, and by different analysts.

**Methods**

We analyzed ~150 archival sedimentary macro-charcoal samples (i.e. recovered from sieves ≥ 150 μm) from three South African grassy ecosystems, together with modern samples prepared using different paleoecological methods. Sites varied in vegetation type and disturbance history. The macro charcoal had been recovered from the standard swirling pollen (Finch and Marchant 2011) and phytolith preparation methods. Retained macro-charcoal samples from different preparation methods and sites with counts visually estimated using the petri dish method were sorted in ascending order. Rank-ordered samples were divided between two research assistants (Enele Twala and Megan Govender). The researchers worked on samples with nearly matching prior macro-charcoal estimates. Samples were sub-sampled using a modified petri dish, (i.e. a 3x4 cell culture plate with 22 mm diameters) to increase the sampling area. Sub-samples were imaged using stereomicroscopes at x50 magnification. Supervised image analysis of charcoal fragments was done with an open-source, edge-detection algorithm, CharTool, in ImageJ (Fig. 1) (Snitker 2020). Samples were blind cross-validated by having researchers reanalyze samples from one another. A subset of validation dataset will be reanalyzed by a senior researcher to complete the cross-validation.

**Outputs**

This work is ongoing as we must analyze and interpret results. In addition, we will test a competing object-based image analysis (OBIA) for batch image analyses. The technique uses a segmentation approach similar to edge detection, and allows objects to be classified based on color, geometry, texture, and context. We will share project outputs and upcoming activities through the International Paleofire Network (paleofire.org), which posts regularly in the *Past Global Changes Magazine* and PAGES Newsletter, and on Twitter (@PaleofireWG). Upon completion, images and data from this project will be publicly available in the Neotoma Paleoecology Database (neotomadb.org).

AFFILIATION

[1]Evolutionary Studies Institute, University of the Witwatersrand, Johannesburg, South Africa
[2]School of Animal, Plant and Environmental Sciences, Johannesburg, South Africa
[3]School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Durban, South Africa

CONTACT

A.N. Dabengwa: abraham.dabengwa@wits.ac.za

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# Paleoecology of mangroves along the Kenyan coast

Christine Omuombo[1,2,3]

**As a PAGES-Inter-Africa Mobility Research Fellow, Dr. Christine Omuombo undertook training, a laboratory exchange and research networking at the University of Cape Town's Stable Light Isotope Laboratory.**

Most of the paleoclimatic reconstructions from East Africa have been obtained from lacustrine and swamp records. These records reveal the effects of long-term climate change and local tectonics linked to the development of the East African Rift System, and the sensitivity to changes in the African monsoonal rainfall belt that migrates with the Intertropical Convergence Zone (ITCZ; Nicholson 1996). These records of past changes have shown the variability in the amount of precipitation over nearly constant temperatures (Bonnefille et al. 1991).

Along the coastal zone, few records exist of the paleoclimatic response of ecosystems. The mangrove forest is one of the most important ecosystems along the Kenyan coast, covering 60% in the Lamu Archipelago within the tidal and intertidal zones (Fig. 1). The sediments in these zones are usually either in-situ, or transported from inland catchments by the Tana river, and distributed along the coast by longshore sediment transport.

### The intertidal zone and organic carbon in the Lamu Archipelago

The intertidal zone is sensitive to global carbon cycle processes driven by sea-level changes. The Lamu Archipelago, a group of low-lying islands with wide intertidal platforms, comprises the old deltaic plains of the Tana River that developed after the last glacial sea-level lowering and subsequent post glacial Holocene flooding of continental shelf and coastal valleys, isolating the island from the delta system (Accordi and Carbone 2016). The aim of the PAGES-Inter-Africa Mobility Fellowship was to carry out the analysis of $\delta^{13}C$ and $\delta^{15}N$ values, total organic carbon (TOC), and total organic nitrogen (TON) content and atomic C/N ratios at the Stable Light Isotope Laboratory at the Department of Archaeology, University of Cape Town, to provide a comprehensive paleoenvironment dataset from sediment samples from the Lamu Archipelago. In addition, the fellowship was also a networking opportunity with research teams at the University of Cape Town (Department of Geological Sciences, The African Climate and Development Initiative, and the Plant Conservation Unit), and with the Iziko Museum.

### The relevance of sediment geochemistry on mangrove paleoecology

The relative sea-level rise variation of the coastal zone in East Africa during the Late Holocene is not well understood. Several attempts have been made to reconstruct Holocene sea-level changes from the relationships between key mangrove taxa along the Tanzanian coast (Punwong et al. 2018), which have shown its utility in estimating low and high magnitude rise during the entire period. Sediments in the intertidal zones, where mangrove forests are found, are carbon sinks currently being studied to help mitigate the effects of climate change, even though the sediment dynamics are not well understood.

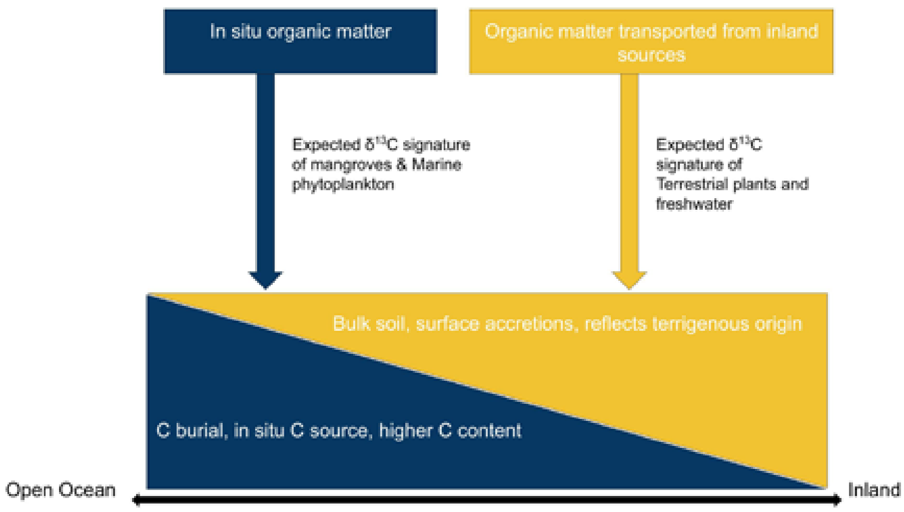


**Figure 1:** Conceptual diagram of organic matter from the intertidal zone. The yellow color corresponds to terrestrial/inland origin of organic carbon, while the blue color represents in-situ produced organic carbon.

### The geochemical analyses at the Stable Light Isotope Laboratory

A total of 50 samples from a sediment core and surface sediments were obtained in the Lamu Archipelago, with the aim of determining coherency of the paleoecological and fluvial dynamics of the coastal zone, and the broad climatic changes. At the beginning of the stay, a laboratory protocol was developed specifically for the sediment samples which are not common at the facility, enabling the preparation of the samples for analysis. This step was followed by training on instrument calibration, sample analysis, and quality control. The energy crisis in South Africa, with frequent rolling blackouts, affected the efficiency and accomplishments of the laboratory analyses. The support from colleagues in the laboratory was very commendable in learning new ways of working and efficiency.

Currently, it is estimated that the analysis of the samples will take another five to eight weeks after the end of the fellowship. These results will be part of a manuscript on the past vegetation changes linked to climatic and sea-level fluctuations, erosion, and changes in anthropogenic land use during the Late Holocene along the Kenyan Coast. Plans are underway to develop joint proposals for future exchanges and partnerships, and to present findings at the East Africa and South Africa Quaternary Associations meeting, and other conferences.

AFFILIATIONS

[1]Department of Geoscience and Environment, Technical University of Kenya, Nairobi, Kenya
[2]Institute for Climate Change and Adaptation, University of Nairobi, Kenya
[3]Department of Earth Sciences, National Museums of Kenya, Nairobi, Kenya

CONTACT

Christine Omuombo: omuomboatieno@gmail.com

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# Phylogenetic diversity in space: A tool to evaluate the effect of paleoclimate on terrestrial biota

Matias C. Baranzelli[1], S. Ramírez-Barahona[2], S.M. Costas[1], A.N. Sérsic[1] and A. Cosacov[1]

**Dr. Matias C. Baranzelli from Argentina, travelled to the Universidad Nacional Autónoma de Mexico as a PAGES-IAI International Mobility Research Fellow, from 18 May–19 August 2022. He studied the response to climate change over the last three million years on flowering plants, mammals, birds and amphibians, considering three levels of biodiversity: genetic diversity, species richness, and phylogenetic diversity. This is an integrating and novel approach to decipher the role of past climate change on current patterns of biodiversity.**

Understanding how paleoclimatic changes have shaped global biodiversity has long been a challenge for biogeographers. In recent years, this has become an urgent goal to improve our ability to predict biodiversity response to global change. Uncovering the relationships between biodiversity and past climate change can provide testable hypotheses about the current and future impacts of ongoing anthropogenic climate change on biodiversity distribution. The impact of different anthropogenic activities on ecosystems is the main cause of the biodiversity crisis (Urban 2015); hence, there is a need for conservation biology to combine taxonomic, evolutionary, and phylogenetic research with ecological research (Eguiarte et al. 1999). In particular, phylogenetic diversity (PD) emerges as a fundamental conservation tool that combines information on species richness and phylogenetic relationships for any given region. In essence, PD is the total branch length of a phylogenetic tree that connects all species in a given group (Faith 1992). An ensemble with more distantly related species will be phylogenetically more diverse than one with species more closely related.

Different aspects of biodiversity are integrated into the PD and provide clues about ecosystem responses to climate change. Species that share a common evolutionary history are expected to have specific ecological traits that may enable them to persist, either in areas with historical climatic instability, or in areas with stable climates (Santos et al. 2022). In either case, species distributions may be significantly altered with each climate cycle, resulting in distribution patterns that are consistent with ecological features and shared phylogenetic signals (Santos et al. 2020). For example, communities within areas that underwent profound past climate change will tend to show species that are more phylogenetically clustered; that is, communities composed of more closely related species than expected by chance. Given this expectation, determining the relationship between phylogenetic diversity and past climate change can prove key to understanding how communities might respond to ongoing climate change. This can help identify priority regions for conservation.

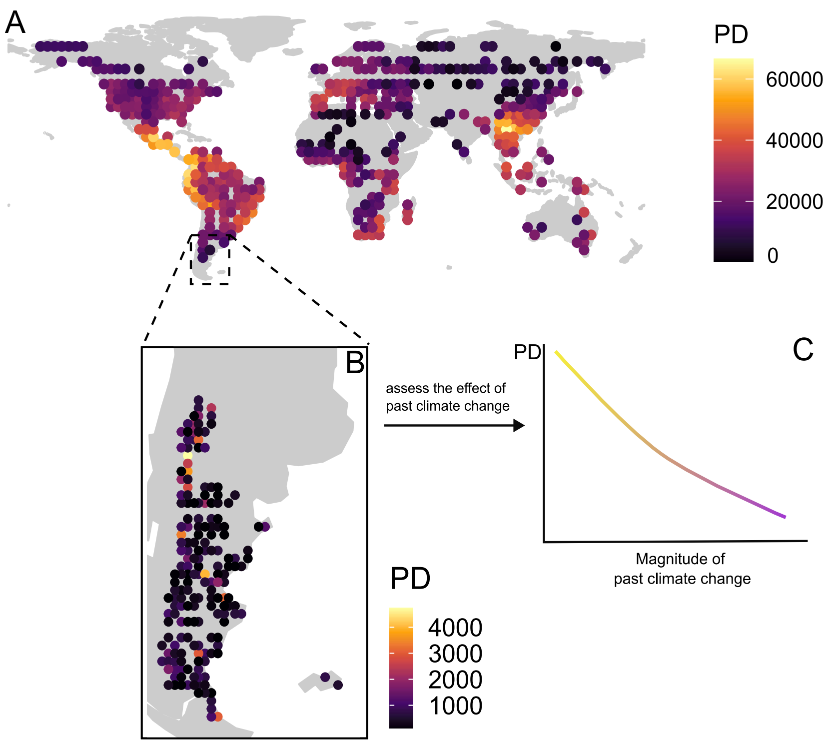


**Figure 1:** Estimation of global **(A)** and regional (Patagonian Steppe) **(B)** phylogenetic diversity (PD) from phylogenetic data and georeferenced records of angiosperm species. Future studies will evaluate PD relationships with past climate change **(C)**.

During the PAGES-Inter American Institute for Global Change Research Fellowship at the UNAM, we estimated the phylogenetic diversity of flowering plants across the globe (Fig. 1a) and across the Patagonian Steppe in South America (Fig. 1b). For this, we used geographic data from Ramírez-Barahona et al. (2020) and Baranzelli et al. (2022), and combined them with the phylogenetic tree developed by Smith and Brown (2018). Our main goal was to evaluate the relationship between phylogenetic diversity and past climate change at different temporal and spatial scales (Fig. 1c). We also estimated phylogenetic diversity for three groups of terrestrial vertebrates across the globe (mammals, birds, and amphibians). The main results of this study were reported at the VII Mexican Congress of Ecology, which took place over the course of the PAGES-IAI Fellowship.

The experience at the UNAM also served to create new research collaboration experiences between different Latin American institutions to evaluate the role of past climate change on biodiversity. By combining the bioinformatic and conceptual capabilities of host and home institutions, it is expected that relevant models will be obtained to understand the effect of past climate change on current patterns of global biodiversity, considering all its dimensions (i.e. genetic diversity, species richness and phylogenetic diversity). We expect to submit the main results to a peer-reviewed journal in the following months.

AFFILIATIONS

[1]Laboratorio de Ecología Evolutiva - Biología Floral, Instituto Multidisciplinario de Biología Vegetal (IMBIV), CONICET-Universidad Nacional de Córdoba, Argentina

[2]Departamento de Botánica, Instituto de Biología, Universidad Nacional Autónoma de México, México

CONTACT

Matias C. Baranzelli: mbaranzelli@imbiv.unc.edu.ar

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# Lake sedimentary DNA research: Extending the *seda*DNA network across Latin America

Marcos E. Echeverría[1] and Bárbara Moguel[2,3]

**Collaboration between Dr. Echeverría and Dr. Moguel was carried out with the support of the PAGES-IAI International Mobility Research Fellowship Program during August and September 2022. This project allowed Dr. Echeverría to explore new insights into ancient DNA (aDNA) and sedimentary DNA (*seda*DNA) analysis, supervised by Dr. Moguel, who has extensive experience in exploring *seda*DNA and working in metagenomic studies at UNAM-Juriquilla, México.**

### Overall process

Paleoecological studies in Latin America provide information about changes in vegetation and climate during the late Quaternary. Analysis of aDNA is a field that is rapidly expanding as a new technique to reconstruct past and modern environments (Capo et al. 2021; Parducci et al. 2018).

Rincón de Parangueo is a crater lake located in the Valle de Santiago volcanic field, central México (Fig. 1). The water level increases during the rainy season and it greatly reduces during the dry season, making this area an example of a fast and drastic transformation environment. Also, Rincón de Parangueo consists of native vegetation and constitutes one of the few natural areas of deciduous tropical forest in central México.

In this context, this site represents an ideal setting to study the microbiota biodiversity in the area through *seda*DNA metagenomic analysis, and to reconstruct past environmental changes. We recovered a 964-cm-long sequence using a Livingstone corer from the Rincón de Parangueo lake. During the fieldwork, emphasis was placed on minimizing sample contamination, because it is critical for performing adequate DNA extraction and analysis. DNA samples were processed in the International Laboratory for Human Genome Research (LIIGH-UNAM-Juriquilla, México). DNA was extracted from 0.25 g sediment samples using the PowerSoil® DNA Isolation kit from QIAGEN, following the manufacturer's protocol. An additional Proteinase K solution (400 µL, 2 mg/mL) per sample was added to complement the lysis process following Epp et al. (2019) modification protocol.

After the DNA extraction was made, the samples were purified using OneStep™ PCR Inhibitor Removal Kit to remove impurities from the samples. For the construction of the genomic libraries we used the NEBNext DNA Library Prep Master Mix Set (New England BioLabs) following the manufacturer's protocol. DNA quantity was estimated using Qubit fluorometric equipment. After the genomic libraries construction, a qPCR was performed. The data obtained from the DNA extraction and metagenomic analysis from the Rincón de Parangueo sediment core will compliment the sedimentological and geochemical information available for this area, and, therefore, will allow us to carry out a more accurate environmental reconstruction, in terms of regional climate change.

Furthermore, Dr. Echeverría gave a seminar at CGEO-UNAM to talk about the collaboration with Dr. Moguel, and to discuss possible future project initiatives involving *seda*DNA in Latin America. After this, there was an opportunity to discuss the outline of a whitepaper on South American *seda*DNA paleoecology and future projects on the same topic. In particular, this future cooperation will focus on performing *seda*DNA analysis to determine the times of colonization and expansion of the south Patagonia Argentina forest after the deglaciation. These results will be combined and interpreted together with pollen records made by Dr. Echeverría. These data will help to determine which tree species were the first ones to expand after the glacial retreat, and also if some of these species may have survived in refugia during cold stages.

**Figure 1:** Rincón de Parangueo crater lake has been exposed to exploitation as a hydric resource by residents of the region over the last 40 years, leading to a gradual drying of the lake.

### Conclusion

The PAGES-IAI Fellowship was a unique opportunity to establish an international *seda*DNA network between Latin American countries, promoting new *seda*DNA projects between México and Argentina. Also, the PAGES-IAI Fellowship enabled the planning of a joint future project in Patagonia, Argentina, where the *seda*DNA analysis will play a key role.

Today, Latin American researchers are still largely underrepresented in the *seda*DNA research community. For this reason, the PAGES-IAI International Mobility Research Fellowship Program represented a great opportunity to increase the number of *seda*DNA projects in Latin America and to empower local researchers to play a central role in lake *seda*DNA research in the near future.

AFFILIATIONS

[1]Instituto de Investigaciones Marinas y Costeras, Universidad Nacional de Mar del Plata, Argentina
[2]Centro de Geociencias Center, Universidad Autónoma de México - Campus Juriquilla, México
[3]Laboratorio Internacional de Investigación sobre el Genoma Humano, Universidad Autónoma de México - Campus Juriquilla, Mxico

CONTACT

Marcos E. Echeverría: echeverriamarcos@mdp.edu.ar

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# Fog-dependent forests in southern Atacama face threat from drought

Paul Szejner[1,2], D.A. Christie[3,4], C. LeQuesne[3] and A.G. Gutierrez[5,6]

**Dr. Szejner was granted a PAGES–IAI Fellowship and worked at the Universidad Autónoma de México from July to August 2022. His goal was to establish and strengthen a collaborative network between tree-ring research groups from México and Chile, and to analyze stable isotopes in tree rings.**

The fog-dependent forest on the southern edge of the Atacama Desert is one of the most fantastic and enigmatic woodlands one will ever see. This ecosystem is formed by patches of temperate rainforest located within a semiarid matrix at the southern edge of the Atacama Desert.

The Fray Jorge National Park is at the top of the coastal mountain range, facing the Pacific Ocean. These forests are relict formations from a past continuous distribution in the Pleistocene (Villagrán et al. 2004). This unique biogeographical landmark has been preserved due to exceptional orographic conditions, allowing for fog formation from the clouds from the Pacific Ocean. The fog is collected by an intricate vegetation structure consisting of the crowns of trees, vines, lianas, ferns, mosses, and fungi (Fig. 1). The condensed and trapped water drops into the soil, allowing the forest to thrive for millennia.

Trees often reach more than one meter in diameter and can be as old as 250 years (Gutiérrez et al. 2008). These forests experience natural changes as part of their inherent development processes, with constant canopy gap formation contributing to their unique structure and composition (del-Val et al. 2006; Gutiérrez et al. 2008). There are two central species dominating this enigmatic forest: the most abundant, olivillo (*Aextoxicon punctatum*), followed by canelo (*Drimys winteri*). These are two dominant species from the evergreen temperate rainforests typically found around 1000 km south of this site.

Thanks to the support from this fellowship, we investigated how the ongoing regional megadrought (MD) in Central Chile (Garreaud et al. 2020) affects the Fray Jorge forests. This interest arises from the generalized concern in the region about the environmental, social, and economic impact of the current drought occurring in Central Chile, which is seen as a forecast of the climatic conditions that will prevail under current climate change scenarios (Cook et al. 2022; Garreaud et al. 2020). Increasingly, dry conditions and rising temperatures threaten forested ecosystems. Therefore, we need a better understanding of how trees respond to the recent regional aridity trends and the local oceanic fog dynamics.

Our objective in this study was to address questions on the effects of the current MD on fog variability and water availability on the forest response in this unique fog-dependent ecosystem. For this, we used conventional tree-ring techniques and stable isotopes (Belmecheri et al. 2022). We conducted our fieldwork in July 2022. We collected tree-ring samples of olivillo to generate new long-term records of tree-ring width chronologies, along with their oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes.

In addition, we organized a workshop at Universidad Austral de Chile to discuss the applications and best practices for interpreting stable isotopes in tree rings. We also organized a series of lectures at the Fray Jorge National Park (La Serena, Chile) for the park rangers and staff to share some past findings, aiming to increase awareness about the effects of climate change on this unique ecosystem.

**Figure 1:** Fog-dependent forests at the southern edge of the Atacama Desert in the Fray Jorge National Park. This olivillo tree (*Aextoxicon punctatum*) has been growing for hundreds of years, falling, sprawling, and re-rooting several times along the way, producing several trunks.

The outcomes of this fellowship will provide insights into the impact of the current MD on these forests, and reconstruct the tree responses of these unique forests in Chile. This effort will help to interpret changes in intrinsic water-use efficiency, vapor-pressure deficit changes, and potential changes in water sources that these fog-dependent forests have been experiencing over the last few decades. Additionally, our collaborative project will strengthen the academic relationship between Mexican and Chilean research centers and universities, promoting studies about climate change and its effects on the biogeochemical cycles recorded in the stable isotopes fixed in wood for centuries. Finally, this project will help initiate a Pan-American research program of stable isotope analyses in tree rings across Latin America.

ACKNOWLEDGEMENTS

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AFFILIATIONS

[1]Instituto de Geología, Universidad Nacional Autónoma de México, Mexico City, México
[2]Bioeconomy and Environment Unit, Natural Resources Institute Finland, Helsinki, Finland
[3]Laboratorio de Dendrocronología y Cambio Global, Instituto de Conservación Biodiversidad y Territorio, Universidad Austral de Chile, Valdivia, Chile
[4]Center for Climate and Resilience Research (CR) 2, Santiago, Chile
[5]Departamento de Ciencias Ambientales y Recursos Naturales Renovables, Universidad de Chile, Santiago, Chile
[6]Instituto de Ecología y Biodiversidad, Santiago, Chile

CONTACT

Paul Szejner: paul.szejner@luke.fi

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# Dendrochronological potential of Tarara colorada (*Platymiscium ulei* Harms) in tropical dry forests of Bolivia

Mónica Vicente

**Bolivian engineer Mónica Vicente visited the dendrochronology laboratory at IANIGLA-CONICET in Mendoza , Argentina, as part of the PAGES-IAI International Mobility Research Fellowship Program. During her stay from March to May 2022 she worked with tree rings and performed growth measurements in relation to the climate of the sampling zone.**

Bolivia has the largest proportion of tropical dry forests in South America. However, there is strong pressure on forest areas due to anthropogenic activity. The highest deforestation rates are concentrated in the lowlands where most of the tropical dry forests are located. Therefore, it is essential to use paleoproxies to understand climatic variation over the last centuries in this region.

Dendrochronology is one of the most common tools used to generate information and reconstruct past climatic variations. In this sense, tree-growth rings, besides providing paleoclimate information, also allow us to understand the growth ecology of new species of great value, such as *Platymiscium ulei*.

The objective of this project was to study the potential of *P. ulei* in dendrochronology in tropical dry forests of Bolivia. Samples of *P. ulei* were taken in the Mercedes Forest management area, in the municipality of Concepción, department of Santa Cruz, Bolivia. The area has a mean annual temperature of 25.4°C and 1150 mm of annual precipitation with marked seasonal droughts throughout the year.

After cross-sections, samples of tree trunks were processed, and the growth rings were dated and measured following standard methods in dendrochronology. The manual dating was performed with the COFECHA program to verify the individual quality of each measurement by detecting and correcting possible dating errors (Holmes 1983). Thereafter, all the samples were standardized with the ARSTAN program (Cook and Holmes 1999).

**Chronology**

The tree-ring chronology corresponds to the period 1923–2015 CE (17 samples). The chronology is replicated by more than 10 trees from 1950 CE, and in 65 years has an autocorrelation of 0.50 indicating a common sign of growth and a mean sensitivity of 0.41, indicating the interannual variability in the width of the rings. Likewise, the chronology has an R-bar (running series of average correlations) of 0.30, which indicates the common growth signal over a period of time, and an EPS (expressed population signal) of 0.85 (Fig. 1a).

EPS is an indicator of the population signal between a given chronology and a hypothetical chronology that has been replicated infinitely for a common time interval, and increases with more trees being incorporated (Wigley et al. 1984). Theoretically, EPS values equal to or greater than 0.85 indicate that the number of samples in the timeline is adequate, and capture an adequate percentage of the signal (Briffa 1999).

**Climate-growth relationship**

The tree-ring chronology starts at 1923 CE and climatological data are only available from 1943 CE onwards. The correlation of growth of *P. ulei* trees with precipitation during the wet season (October–March) is positive (r= 0.48; $p<0.005$) from 1943–2015 CE (Fig. 1b). The mean annual temperature for the same period has an inverse, but significant, correlation with growth rate (r=-0.25; p<0.005). The latter is explained by the higher temperatures that increase evapotranspiration, intensifying water deficit, and reducing radial growth (López and Villalba 2016).

The presence of growth rings in trees with annual periodicity is imperative for dendrochronological studies in tropical regions. In this sense, *P. ulei* trees in the Mercedes Forest present distinguishable rings with a similar growth pattern. Therefore, dendrochronological analysis can contribute to a better understanding of regional climate variability and its impact on the fragile ecosystems from which this species originates. The trees of this species capture a significant variation in the dominant climatic conditions of the area, which constitutes a premise for studies with dendroclimatic applications and, in turn, answers paleoclimatological and paleoecological questions prioritized by the paleoscientific community.

AFFILIATION

Faculty of Agricultural Sciences, Gabriel René Moreno Autonomous University, Santa Cruz de la Sierra, Bolivia

CONTACT

Mónica Vicente: monicavicente@uagrm.edu.bo

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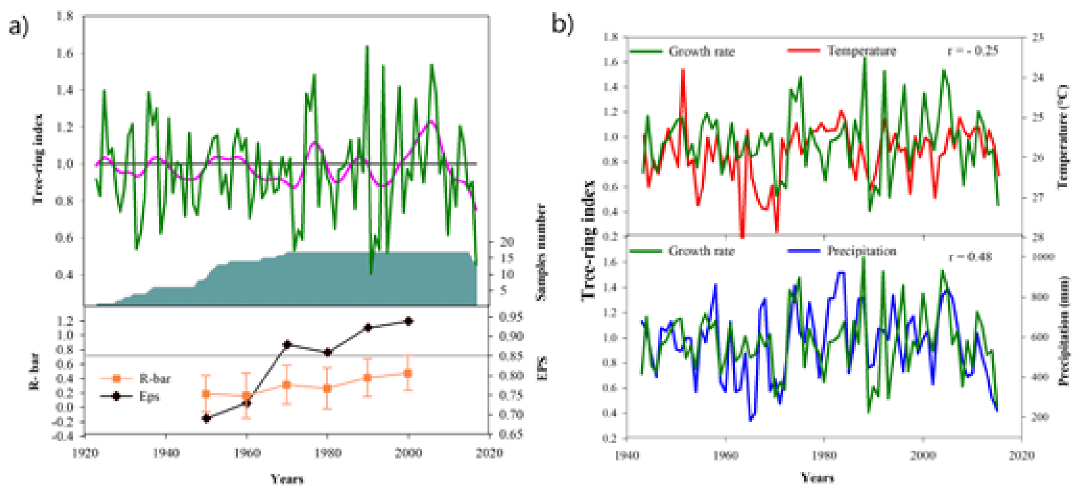


**Figure 1: (A)** Standard chronology (top) 1923-2015 CE and number of *P. ulei* trees analyzed (middle). Statistics assessing the quality of the chronology using the values of EPS and R-bar over time (bottom). **(B)** Comparison between tree-ring growth rate and interannual variations of temperature (top) and precipitation (bottom) for the period 1943-2015 CE.

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# Challenges and opportunities of communicating interdisciplinary paleoscience: An early-career researchers' perspective

Giorgia Camperio[1,2], M.E. Castiello[3], I. Jara[4], T. van Kolfschoten[5], K. Marcisz[6] and D. Moraga[7]

In times of environmental crisis, effectively communicating scientific results to the wider public is of paramount importance (Fischhoff and Scheufele 2014). The ability of early-career researchers (ECRs) to make research accessible to different interest groups can increase opportunities for career development (Wright and Vanderford 2017).

Challenges and opportunities of communication are amplified in interdisciplinary projects, such as those addressing past socio–environmental systems (PASES) (Benito et al. 2021). Here, we compare experiences among participants of the PAGES-INQUA ECR PASES workshop, to address the overarching question: does an ECR need to be an octopus to communicate interdisciplinary paleoscience? To answer this question, we focused on three topics: research, funding, and outreach (Fig. 1).

**Research**

Paleoscience spans a wide range of different domains, and scholars often work interdisciplinarily. Publishing pressure is particularly high for ECRs (van Dijk et al. 2014). Working interdisciplinarily requires additional time investments to keep up with new literature, while the few interdisciplinary journals available challenge research sharing, and can hinder career advancement.

Communication in research is key for the success of interdisciplinary projects. However, researchers working interdisciplinarily have to overcome semantic differences encountered in the specialized language of each domain. In this context, it can be challenging to communicate interdisciplinarily at field-specific conferences, but workshops organized by ECRs for ECRs (see the workshop report by Benito et al. on p. 48 of this issue) can be a perfect setting to exchange ideas and set the initial stage to develop collaborative projects.

**Funding**

ECRs are caught in a loop between funding agencies and journals, where successful grant applications depend on the quality of publications, which in turn require funding to produce data. Stakes are high for ECRs who are usually under non-permanent contracts. Proposal writing challenges are common across fields, requiring an equilibrium between details and the broader picture. Interdisciplinary proposals should highlight how each discipline is crucial to answering the research questions and demonstrate the impact of research on broader issues.

Although interdisciplinary proposals allow researchers to access funding schemes that are not available to single-discipline research projects, ECRs working in low- and middle-income countries, where institutions might lack grant advice offices, can face difficulties in accessing funding schemes (e.g. ERC grants). Being part of an ECR network (e.g. PAGES Early-Career Network) can be an advantage, as members can share information and experiences, and sometimes online resources are available (e.g. webinars, see PAGES ECN YouTube channel: youtube.com/PAGESECN).

**Outreach**

Communication to the public is a transferable skill increasingly valued by institutes, funding agencies, and journals. Plain language abstracts in scientific journals exemplify the different communication styles required to engage with a broader audience: scientifically accurate without excessive technical detail. Storytelling helps to raise interest in complex research topics, but it is not something scientists are trained for.

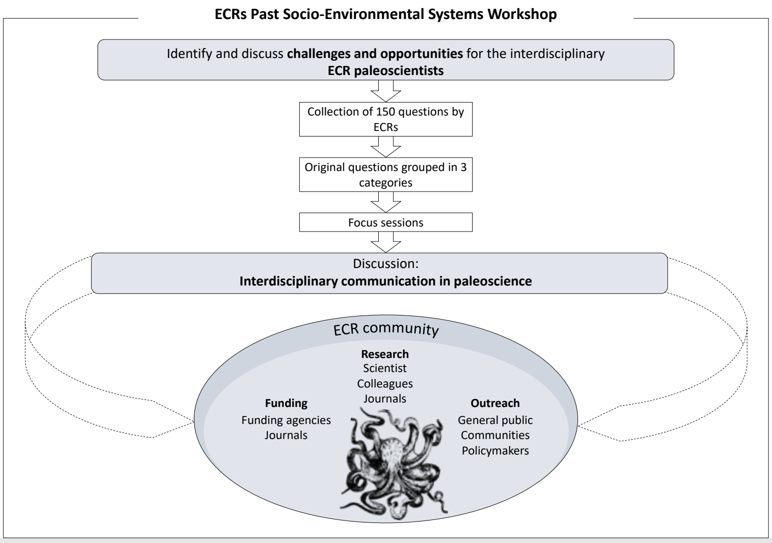


**Figure 1:** Methodological framework and discussion outcomes (symbol attribution CC0 1.0 svgsilh.com/image/1296937.html).

Paleoscience can deal with strong barriers in outreach (e.g. climate-change deniers), but topics related to PASES can be less challenging to communicate compared to other interdisciplinary topics. They can capture the attention of the audience by highlighting how paleoscientific research connects with pressing environmental issues (Razanatsoa et al. 2017). Furthermore, most ECRs might be at ease sharing their findings on social media platforms. Nevertheless, it may become overwhelming to keep up with different social media platforms. The ECR community can help, e.g. sharing publication posts to specific working networks that reach a larger audience (e.g. @PAGES_ECN).

**Conclusions and recommendations**

In the three domains of science communication that concern ECRs working on interdisciplinary subjects, challenges outnumber opportunities.

Our discussion is not new to ECRs in paleoscience (e.g. Plumpton et al. 2017, Roop and Dietze 2013) and is not meant to provide solutions. We highlighted aspects that emerged during our focus session, realizing that despite our different backgrounds, we shared common challenges.

Pressure on ECRs is high, mental health is at stake, work-life balance is often precarious, and time is limited. It is not required to master each of these communication aspects, but rather acknowledge their existence and focus on the opportunities. ECRs do not have to be octopuses; they can rely on a community to complement each other.

AFFILIATIONS

[1]Department of Earth Science, ETH Zürich, Switzerland
[2]Department of Surface Waters, Research & Management, Eawag, Dübendorf, Switzerland
[3]Institute of Archaeological Sciences (IAW), University of Bern, Switzerland
[4]Department of History and Geography, University of Tarapacá, Arica, Chile
[5]Faculty of Archaeology, Leiden University, Netherlands
[6]Climate Change Ecology Research Unit, Adam Mickiewicz University, Poznań, Poland
[7]Ecology Department, Pontificia Universidad Católica de Chile, Santiago, Chile

CONTACT

Giorgia Camperio: giorgia.camperio@eawag.ch

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# Advice on how to organize an ECR workshop – lessons learned during PASES 2022

PASES workshop organizers*

During the three years leading up to the PASES 2022 workshop (pastglobalchanges.org/calendar/26972), the organizers gained valuable knowledge in workshop organization and want to share this with future early-career researcher (ECR) workshop organizers.

**1. Bottom-up approach**
The initiative should derive from ECRs themselves, who wish to bring people together with similar research interests, visions for collaboration, and career-stage concerns. Associations like INQUA and PAGES may provide funding and guidance.

**2. A diverse and strong team**
Our experience shows that diversity in culture, research background, and career stage contribute to creative and well thought out decisions. Success requires that everyone listens carefully to all voices and opinions, and that decisions are made in a democratic and pragmatic way. Once issues are discussed in-depth, decisions are often much easier to make, and defend.

**3. Community surveys**
Before launching a workshop, a short survey asking for information on, for instance, career stage, research interests, and potential contribution and expectations of the workshop can be used to evaluate the interest to participate in the workshop.

**4. Organization logistics**
The costs of the workshop (including lunch and coffee breaks, excursion, formal dinner, accommodation, travel costs, small items, and consumables) should be estimated carefully and with a 10–15% buffer. The venue should be chosen considering practical issues, like space, and technical facilities that allow for hybrid events. Pre-recorded talks reduce technical issues and complications due to time-zone differences and travel restrictions. Visa applications should be initiated as early as possible, and one should be prepared for (last-minute) cancellations.

**5. Dedication**
Event organization entails great personal commitment and is time consuming, e.g. frequent meetings over long time periods, selecting and keeping in contact with participants, and creating an interesting, meaningful, and diverse program.

**6. Communication**
Communication between organizers and with the participants is crucial. Here, frequent meetings with a written record on decisions made, and platforms for document sharing that can easily be accessed by everyone, are essential. Further, clear and timely communication about the workshop's topic, target group, format, outcome, registration/application/selection procedures (e.g. definition of ECR), and deadlines is important.

**7. Selection of participants**
A system on how to rank applications in a balanced (including geographic and gender distribution), independent, and efficient way should be developed beforehand. Further, a structure in which each abstract is graded, based on criteria such as fit of topic, novelty, and research quality, can be helpful. Financial support is essential to facilitate participation of ECRs from low-income countries.

**8. Networking**
Interaction and networking are key elements of a workshop, and sufficient time should be allocated. Breakout activities are an established method to foster fruitful discussions. Here, it is important to communicate the goal clearly so that all participants know their role. Not only scientific, but also more general topics (e.g. "the challenges of being an ECR") provide a good basis for discussions. Other ways to combine knowledge growth and communication between participants, and create time to relax, are social gatherings and field excursions.

**9. Involve locals**
Involving local undergrad students will give them the chance to get closer insights into research, join a scientific community, take responsibility, and show engagement. They can be key for solving problems on site by overcoming language barriers. Further, cultural and scientific exchange with local students is an added value for both participants and organizers.

**10. Outreach talks**
Outreach talks can be organized to give a broad audience the chance to be involved in scientific activities. They are a good exercise for ECRs to present and receive feedback from people outside their research area.

**11. Wrapping up, and the end?**
At the end, certificates need to be handed out, finances consolidated, the event reported on, the results from breakout activities summarized, and then the workshop is over. But is it really over? Ideally, the established network becomes a base for long-term research collaborations, including the organization of further conference sessions or workshops.

AFFILIATIONS
*See the online version for the complete author list

CONTACT
Anna-Marie Klamt: amklamt@outlook.de

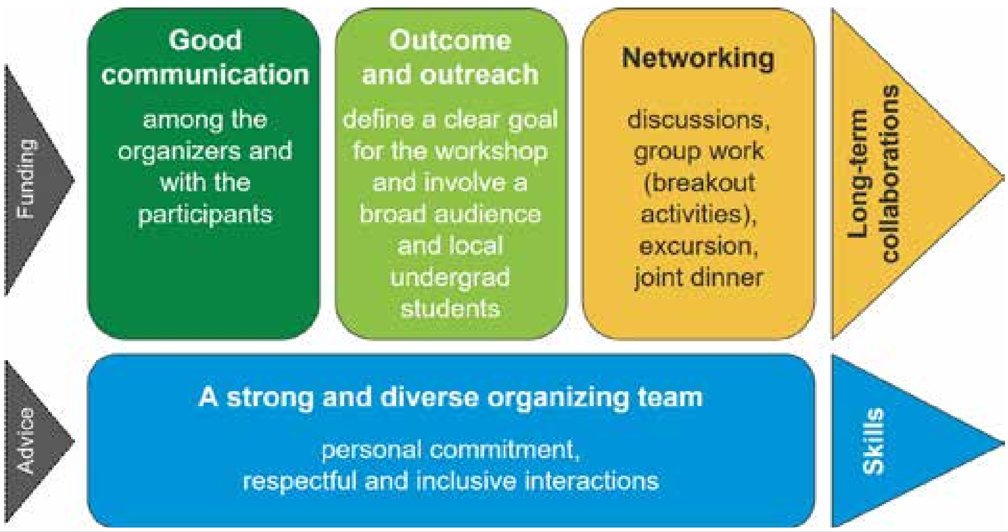


**Figure 1:** Schematic overview about important aspects needed to organize an ECR workshop. Note, ideally one gets more out of (triangles on the right) than one puts into (triangles on the left) an ECR workshop.

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# The warm Pliocene: Bridging the geological data and modeling communities

Heather Ford[1], A. Dolan[2], A. Haywood[2], E. McClymont[3], L. Pérez-Angel[4] and L. Burton[2]

**PlioMioVAR workshop, Leeds, UK, and online, 24–26 August 2022**

PlioMioVAR paleoclimate community and Pliocene Modeling Intercomparison Project (PlioMIP) had a hybrid meeting with in-person participants at Weetwood Hall in Leeds, UK, to present recent work and plan future PlioMioVAR working group (WG) (pastglobalchanges.org/pliomiovar) and PlioMIP3 objectives. The meeting was a European Geoscience Union Galileo Conference with additional funding from PAGES and UK-IODP. PlioMioVAR plans to build on the successful first phase of the former PAGES PlioVAR WG (pastglobalchanges.org/pliovar) by including the Miocene, and develop data-model comparison targets with the PlioMIP3 and Deep-Time Model Intercomparison Project (DeepMIP) Miocene Group. Approximately 100 working group members gathered in-person (55) and online (45) to cover a breadth of expertise in paleoceanography, corals and speleothems, paleobotany, and climate modeling.

**(1) From PlioVAR to PlioMioVAR**

As our initial phase of the PlioVAR database is nearing completion (McClymont et al. 2020), built as part of the former PAGES PlioVAR WG, our ongoing aim is to expand the dataset spatially and temporally. The first phase of PlioVAR focused on marine records due to the specific age-model constraints for data-model comparisons. Consequently, terrestrial archives of vegetation and precipitation were excluded from the initial work. Workshop participants identified updating the terrestrial records as a strategic aim of the next PlioMioVAR objectives. The Miocene arm of the working group met in January 2023, and has a series of planned hackathons before a hybrid meeting in June 2023 (pastglobalchanges.org/calendar/129302) to work on organizing paleoceanographic records.

**(2) From PlioMIP2 to PlioMIP3**

The second phase of the Pliocene Model Intercomparison Project (PlioMIP2) is reaching its conclusion, with meeting participants presenting various paleoclimate modeling studies covering topics such as the quantification of Earth's Climate Sensitivity, patterns of atmospheric and oceanic circulation, polar amplification, climate extremes and assessments of model performance vis-à-vis marine and terrestrial proxy data (Fig. 1). In addition, draft science plans for PlioMIP3 were presented, discussed, and endorsed by participants both from the modeling and data communities. Future modeling directions discussed include the expansion of the temporal remit of PlioMIP into the Early Pliocene, enabling a comparison between Late and Early Pliocene climate states, and building one half of a scientific bridge that will eventually facilitate research collaboration between the PlioMIP and MioMIP projects.

**(3) Fostering a vibrant community**

We purposefully ran our workshop in hybrid mode to include as many people as possible. Although many parts of society are opening up for in-person activities, many of our colleagues do not feel comfortable traveling for medical reasons, or simply wish to travel less due to caring responsibilities, and to reduce carbon footprints. We saw providing a high-quality hybrid option as an equity issue. To enable our hybrid participation, we had a dedicated virtual poster session with individual Zoom rooms for synchronous participation. Each poster had a virtual wall on Padlet (padlet.com) for asynchronous participation and follow up comments. Each Padlet wall included the abstract and poster, and presenters were encouraged to include a brief video explaining their main points, any relevant manuscripts/preprints and/or any other information. Discussion groups were facilitated in-person or on Zoom (not mixed), while for the final reporting, both virtual and in-person groups came together. Talks were a mix of virtual and in-person, and recorded for storage online for three months post workshop. We also ran a session dedicated to discussing Equality, Diversity, and Inclusion that was facilitated by Prof. Mea Cook (Williams College, USA) and an early-career researcher event.

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AFFILIATIONS

[1]Queen Mary University of London, UK
[2]Leeds University, UK
[3]Durham University, UK
[4]Brown University, USA

CONTACT

Heather Ford: h.ford@qmul.ac.uk

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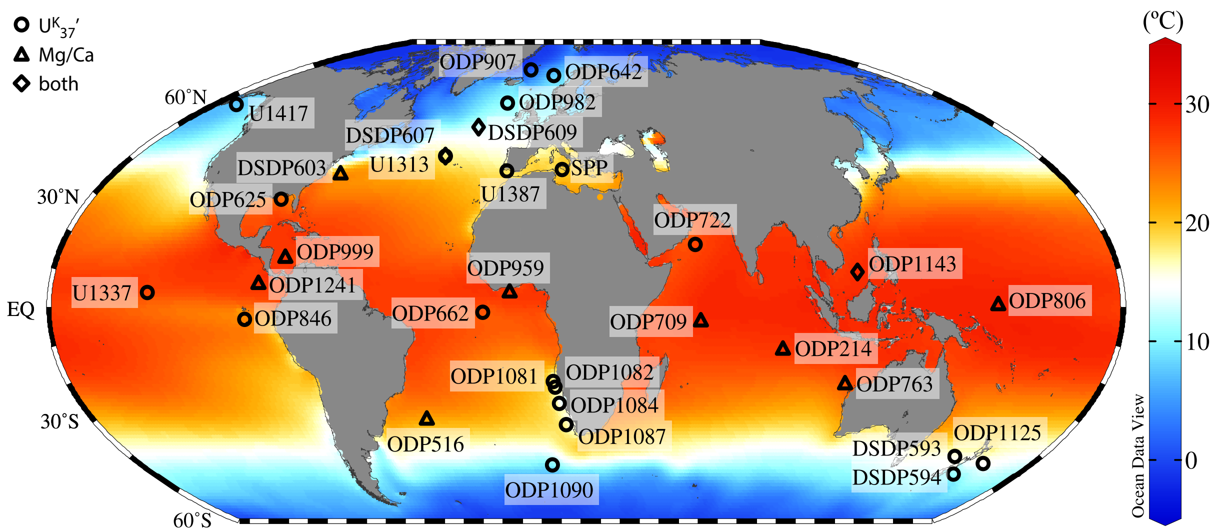


**Figure 1:** Figure from McClymont et al. (2020) showing the site locations used in the PlioVAR synthesis. Sea-surface temperature proxies are indicated with different symbols and the background temperature is from World Ocean Atlas 2018 (Locarnini et al. 2018).

 

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# Numerical ecology and time series analysis of marine proxy data

Sofia Ribeiro[1], M. Heikkilä[2], K. Weckström[1,2] and A. Pieńkowski[3]

**ACME workshop, Copenhagen, Denmark, 14–16 November 2022**

The ACME (Arctic Cryosphere Change and Coastal Marine Ecosystems; pastglobalchanges.org/acme) working group held its second workshop from 14–16 November 2022 at the Geological Survey of Denmark and Greenland (GEUS), in Copenhagen, Denmark. The workshop "Numerical ecology and time series analysis of marine proxy data" focused on statistical treatment of sedimentary proxy data and correct data handling as a foundation for accurate and robust paleoenvironmental and paleoclimatic reconstructions.

The overarching aim of ACME is to assess and refine available marine proxies in the Arctic coastal zone. A particular focus is placed on the techniques (field, analytical and numerical) and the quality of data, on the establishment of new community-driven protocols and on the training of early-career researchers (ECRs). The ACME Community Survey, carried out in late 2020, revealed that nearly half (45% of respondents) of the community consider that we do not, yet, have adequate methods for the quantitative determination of widely reconstructed environmental parameters, and over half (65% of respondents) consider that we do not currently have an adequate understanding of proxy behavior (Heikkilä et al. 2022). There seems to be a misalignment between the statistical knowledge of method users and method developers, which often precludes a more critical evaluation of the approaches used by the community.

This ACME workshop aimed to overcome this challenge by inviting an expert in numerical ecology with extensive experience in paleoecological proxy data and paleocommunities. Dr. Gavin Simpson, professor in applied biometrics at Aarhus University, Denmark, has over two decades of experience in quantitative environmental science across timescales, with a specific focus on aquatic environments and complex environmental problems. He has developed several R packages, and worked with large databases (e.g. Neotoma).

During the workshop, Dr. Simpson shared his knowledge, discussed possibilities and common pitfalls related to numerical approaches in paleoecology, and here, specifically, coastal paleoceanography. In addition, hands-on tutorials and computer exercises using representative coastal data sets were provided, to serve as a real-world training, especially directed at ECRs with some prior experience in using R software.

The workshop included 22 participants from eight different countries (Canada, Denmark, Finland, Iceland, Italy, Poland, Portugal and UK) of which 16 (73%) were ECRs. The majority of participants were female (68% female/32% male). Altogether, the participants covered a broad range of proxy methods, ranging from different groups of microfossils (diatoms, dinoflagellate cysts, foraminifera), biogeochemical markers, and environmental DNA (eDNA). The participants unanimously expressed the wish to become more familiar with data handling, visualization, and numerical methods used to interpret and reconstruct past climate and environmental changes based on proxy data.

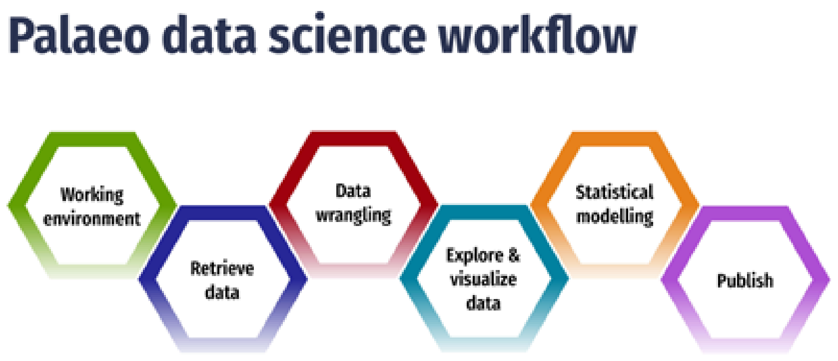


Figure 1: Diagram showing the workflow in data science. Image credit: Gavin Simpson and Steve Juggins.

The first day of the workshop (14 November) was dedicated to an overview of R studio and data handling in R, including the Tidyverse collection of packages, importing data, data wrangling, and visualization. At the end of the first day, Dr. Nicolas van Nieuwenhove (University of New Brunswick, Canada) gave an invited lecture on the Neotoma database and efforts to migrate the widely used Northern Hemisphere modern dinoflagellate cyst reference dataset there. He provided a historical perspective on the use of dinoflagellate cysts in Northern Hemisphere paleoceanography and an overview of the current practices using quantitative methods.

The second day of the workshop was dedicated to multivariate ordination methods (unconstrained and constrained ordination), generalized additive models (GAMs), and their use in ecological modeling, in particular to identify rates and periods of change in time series. The participants had the opportunity to work with their own datasets and discuss the outcome of the analyses.

The third and last day of the workshop was dedicated to quantitative paleoenvironmental reconstruction methods and the assessment of reconstruction validity and accuracy. The different types of paleoecological transfer functions were covered, including weighted averaging-based regressions and the modern analogues technique, as well as evaluation of model performance and diagnostics.

Key take home messages from this workshop were the importance of carefully considering study and sampling design ahead of numerical analyses (e.g. number of samples, replicates, environmental gradients), and the importance of critically assessing proxy data (e.g. what are species responding to?, what processes affect the formation and preservation of this proxy?) beyond statistical and method knowledge.

All the course materials and tutorials are publicly available at: github.com/gavinsimpson/acme-stats

AFFILIATIONS
[1]Department of Glaciology and Climate, Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark
[2]Environmental Change Research Unit (ECRU) Ecosystems and Environment Research Programme, Faculty of Biological and Environmental Sciences and Helsinki Institute of Sustainability Science (HELSUS), Helsinki, Finland
[3]Institute of Geology, Adam Mickiewicz University, Poznań, Poland

CONTACT
Sofia Ribeiro: sri@geus.dk

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# A synthesis of Cenozoic paleoceanographic proxies for seawater oxygenation

Dharma Reyes Macaya[1,2,3], K. Nilsson-Kerr[4], J. Cardich[5], C. Davis[6] and B. Hoogakker[1]

**Bergen, Norway, 3 September 2022**

### Workshop motivation and aim

Deoxygenation is a pressing problem in the world's oceans, impacting global biogeochemical cycles and marine ecosystems. Oxygen time series only span decades (a maximum of ~60 years at their longest), and touch upon a small subset of at-risk ecosystems. The use of paleo-oxygen proxies allows us to explore long-term oxygen trends, including the scope of natural variability and response to warming, and ultimately to inform model simulations and projections.

While interest in paleo-oxygen reconstructions has been rapidly growing, our current proxy landscape often poses limitations. There are multiple established and emergent proxies available, but their scope, limitations, and relation to one another are often poorly constrained.

The aim of the PLO2P (Proxies for Low Oxygen Paleoenvironments) Workshop in Bergen, Norway, in September 2022 (pastglobalchanges.org/calendar/128968), was to convene and build a community of scientists working on paleo-oxygen proxies to begin to address these limitations in a way that was accessible to the larger paleoceanographic community, and collectively map a way forward. Together we decided to begin a review of the state-of-the-art in established and emergent Cenozoic paleoceanographic proxies used for assessing seawater oxygen concentrations.

### Workshop structure

The workshop was held in a hybrid mode to allow for broader participation, with a total of 33 participants. Hybrid mode was particularly useful because some in-person participants had to self-isolate due to COVID-19, but were still able to access the meeting from their conference accommodation. There was a focus on inclusion of early-career researchers (ECRs) actively working with paleo-oxygenation proxies. In total, 19 ECRs attended the workshop, and were also well-represented among the organizing committee (Dharma Reyes Macaya, Katrina Nilsson-Kerr, Jorge Cardich). Five ECRs received funding from PAGES to support their in-person participation at the workshop.

Following introductions, participants joined two (a morning and an afternoon) breakout sessions, based on the proxies they wished to focus on (see Figure 1 for a schematic). Established proxies for oxygen reconstructions include sedimentary features, like laminations, planktic and benthic foraminifera assemblages, sedimentary redox trace elements, and bulk nitrogen isotopes. Emerging paleo-oxygen proxies include the morphology of benthic and planktic foraminifera, benthic foraminifera carbon isotope gradients, benthic and planktic foraminifera trace elements, planktic foraminifera bound nitrogen isotopes, and biomarkers. Many of the proxies may be used for bottom or pore water oxygenations, but, increasingly, proxies are being developed to reconstruct water column oxygen concentrations. Multiple experts on each proxy type were invited to lead and moderate the breakout group sessions. Every section was tasked with identifying recent developments, limitations, and current questions of their proxy type. For example, several sessions identified the need to reconcile proxies developed in restricted basins, with open ocean settings, and vice versa.

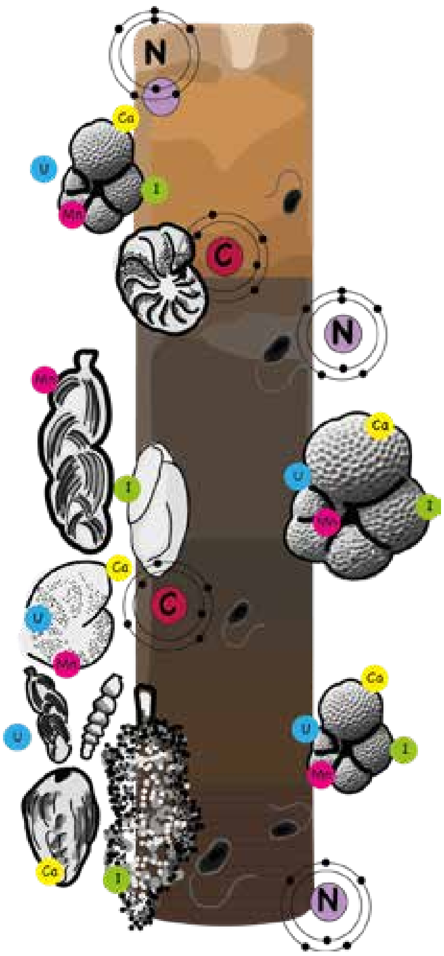


**Figure 1:** Schematic illustration, made by Katrina Nilsson-Kerr, featuring the various paleo-oxygen proxies within a marine sediment core that were discussed during the meeting and will be covered in the review paper.

### Outcomes

The group identified several areas for development. Most proxies are currently only applicable to very low oxygen environments. Moreover, most proxies are qualitative rather than quantitative in nature, but steps are being taken to develop proxies more quantitatively and provide error assessments. The group concluded that more robust assessment of past seawater oxygen concentrations require multi-proxy analyses.

We are formalising our review in a paper using the framework established in the workshop (submission to *Biogeosciences* in August 2023). That review is now well underway, and the number of contributing authors has increased to include authors beyond the initial workshop participants who are experts on some of the proxies included in the review. The review will include descriptions of use and recommendations for best practices by proxy type, guiding those wishing to use paleo-oxygen proxies, and a roadmap for continuing expansion of this field.

Finally, we introduced the idea of forming a working group during the workshop, and are actively working on a PAGES working group proposal for past seawater oxygen assessments through paleoceanographic reconstructions and modeling.

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AFFILIATIONS
[1]The Lyell Centre, Heriot-Watt University, Edinburgh, UK
[2]MARUM-Center for Marine Environmental Sciences, University of Bremen, Germany
[3]ANID-Millennium Science Initiative Program Nucleo Milenio UPWELL, La Serena, Chile
[4]Department of Earth Sciences, University of Bergen and The Bjerknes Centre, Bergen, Norway
[5]Benthic Ecology and Paleoceanography Laboratory, Universidad Peruana Cayetano Heredia, Lima, Peru
[6]Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, USA

CONTACT
Babette Hoogakker: b.hoogakker@hw.ac.uk

 

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# Boron-$CO_2$ workshop: Testing and extending the limits of the foraminiferal boron proxy for seawater pH and atmospheric $CO_2$ reconstructions

Eleni Anagnostou[1], T. Babila[2], T. Chalk[3], M. Henehan[4,5] and M. Raitzsch[6]

**Bergen, Norway, 4 September 2022**

Atmospheric carbon dioxide ($CO_2$) is the key driver of global temperatures over geological time, but calculating the exact sensitivity of Earth's climate to $CO_2$, and hence the trajectory of anthropogenic climate change, requires accurate quantification of past $CO_2$. Determining past $CO_2$ and fluxes among Earth's carbon reservoirs is difficult, particularly prior to ice-core records of the last 800 kyrs. Attempts have been made to compile multi-proxy atmospheric $CO_2$ proxy data through time (Foster et al. 2017; Hönisch 2021; Rae et al. 2021) which have gained considerable traction, including in the Intergovernmental Panel on Climate Change reports (IPCC 2021). However, many of these compilations can include inaccuracies and apparent contradictions arising from differing assumptions and auxiliary inputs used when translating proxy data to $CO_2$. To move forward as a community, ensuring the robustness of future $CO_2$ data contributions and reducing noise in a crucial dataset, such inconsistencies must be minimized, and uncertainties systematically accounted for (Fig. 1).

## The importance of the boron isotope $CO_2$ proxy

Amongst proxies for past atmospheric $CO_2$ reconstruction, boron isotopes have become one of the most well-established, and are increasingly recognized for their accuracy and precision (IPCC 2021). Boron isotopes have gained this reputation for two reasons: firstly, they can replicate atmospheric $CO_2$ during periods where ice-core estimates are available for comparison (Chalk et al. 2017), and secondly, their methodological basis is now reproducible and accurate by different laboratories (Gutjahr et al. 2020) based on community-led efforts to standardize analytical data generation. As yet, however, no analogous consensus has emerged on how we obtain $CO_2$ estimates from boron isotopes. This area has seen a great many advances: in constraining and calculating seawater temperature and boron isotope composition, in deriving the necessary second carbonate system parameter, in how "vital effects" (i.e. biological modifications to the proxy) are accounted for, in dealing with changing seawater chemistry, and in how uncertainties are measured and propagated. As a result of this rapidly changing landscape, many studies are now mutually inconsistent in their guiding assumptions, and old data need updating with new methods, or even replacing or omitting where their inclusion no longer adds value.

## A community-led consensus

To address these issues, we organized a virtual series of workshops between 2021 and 2022, culminating in a PAGES-supported workshop in Bergen, Norway, in September 2022. Our aims were to critically evaluate the approaches used, discuss how to expand the horizons of the boron-$CO_2$ proxy, and build an internally consistent compilation of long-term pH and $CO_2$ change that provides reliable, accurate and future-proof (where possible) constraints on past climate. Several important observations were developed over the course of these workshops, most notably that:

1) although not the main cause of inconsistent $CO_2$ values in the literature, differing data processing scripts utilized by the community can cause reconstructions to diverge over periods of changing seawater composition;

2) a consistent approach to "vital effects" is required to integrate different datasets; and

3) there are critical time periods where data density is poor, such as the Paleocene, Oligocene, and Miocene.

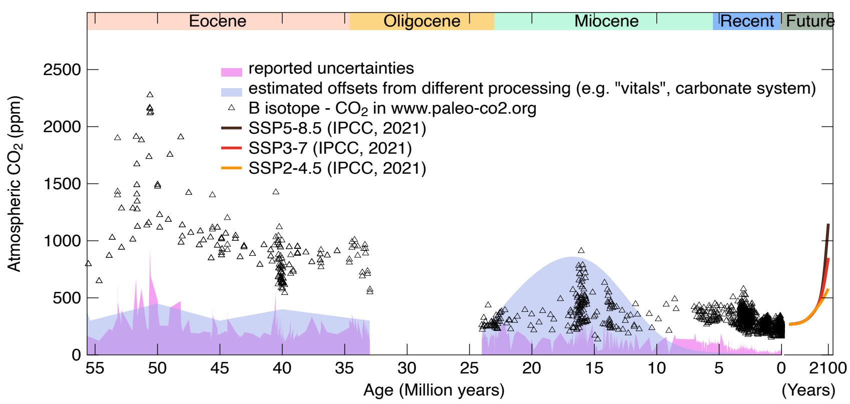


**Figure 1:** Representation of the magnitude of offsets and uncertainties in boron-$CO_2$ estimates in the literature. Future emission scenarios are depicted with lines (IPCC 2021).

Already, these workshops have streamlined cross-platform, community-tested scripts, incorporating recent developments in carbonate and seawater chemistry (Hain et al. 2015). We interrogated the unknowns of the proxy and best-practice approaches, for example the treatment of "vital effects", impact of seawater major ion chemistry, and assumptions about the auxiliary data required for converting pH to $CO_2$. Two periods – the Miocene and the Eocene – were identified as having the largest discrepancies in $CO_2$ estimates, thus providing effective test cases for developing consensus in boron-derived $CO_2$ processing.

Alongside resolving internal inconsistencies within the community, our workshop aimed to look outwards, and foster exchange with the broader community, toward data-model integrations and constraining past carbon cycle-climate interactions and Earth's climate sensitivity. Finally, we demonstrated the need for, and sowed the seeds of, closer collaboration and coordination within the international boron isotope community. Results of these efforts arising from the online and in-person PAGES meetings are already appearing in a dedicated special issue of *Paleoceanography and Paleoclimatology*, which is open for submissions. Results will also be synthesized in a forthcoming boron-$CO_2$ compilation paper.

AFFILIATIONS

[1]GEOMAR, Helmholtz-Zentrum für Ozeanforschung Kiel, Germany
[2]Southampton University, UK
[3]Aix Marseille University, CNRS, IRD, INRAE, CEREGE, Aix-en-Provence, France
[4]German Research Centre for Geosciences GFZ, Potsdam, Germany
[5]School of Earth Sciences, University of Bristol, UK
[6]MARUM, University of Bremen, Germany

CONTACT

Eleni Anagnostou: eanagnostou@geomar.de

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# Human traces in lake sediments: Towards a database for extracting regional signals

Madeleine Moyle[1], J. Massaferro[2], É. Saulnier-Talbot[3] and N. Dubois[4]

**Human Traces workshop, Bariloche, Argentina, 3 December 2022**

What is a human trace and how does it manifest in the environment? Since its inception in 2021, members of the Human Traces working group (WG) (pastglobalchanges.org/human-traces) have been exploring possible answers to this complicated and multifaceted question through a series of online workshops and lectures (recordings are available on our YouTube channel here: shorturl.at/dghW7).

In December, we continued these discussions at our first in-person workshop which was held in Bariloche, Argentina, following our Human Traces in the aquatic sedimentary record session on 3 December at the International Association of Limnogeology and International Paleolimnology Association (IAL-IPA) 2022 Joint Meeting (pastglobalchanges.org/calendar/129293).

The workshop was attended by 20 people from 11 countries, including nine early-career researchers (ECRs), with strong representation from Latin America. This was the occasion to establish a subgroup made up of members from this region, with the aim of crafting an in-depth regional review of human traces in Central and South America (Fig. 1).

This subgroup is open to anyone who has an interest, and can contribute to, the topic. It is coordinated by Human Traces WG member Julieta Massaferro (jmassaferro@comahue-conicet.gob.ar), who can provide further information about the initiative for those interested.

Attendees at the workshop also discussed plans to start working on a synthesis on the subject of reservoirs and the long-term development of anthropohydrocosms (a human-made body of water) (Saulnier-Talbot and Lavoie 2018) as agents of human traces in the environment.

The tentative objective of this subgroup would be to assess the use of the paleolimnological approach to evaluate and quantify anthropogenic impacts on the environment through time, via the creation and modification of aquatic ecosystems. This project is co-led by ECR Léo Chassiot (leo.chassiot.1@ulaval.ca) and WG coordinating member Émilie Saulnier-Talbot (emilie.saulnier-talbot@bio.ulaval.ca). All paleoscientists interested in participating are welcome to get in touch.

Finally, the workshop was also the occasion to update participants on the progress made by the lead proxy subgroup, who have already held an online workshop to develop a synthesis of lead as an indicator of human traces in sedimentary archives.

ECR Madeleine Moyle (maddy.moyle@liverpool.ac.uk) and WG coordinating member John Boyle (jfb@liverpool.ac.uk) are co-leaders of this subgroup. They held an online meeting in April 2023 and are planning an in-person meeting this year, with a provisional date in September 2023.

The group is currently collecting data and is working closely with the Neotoma community on developing a database for geochemical archives in lake sediments. If you have anything to contribute, please contact the co-leaders of the Human Traces WG (pastglobalchanges.org/science/wg/human-traces/people). For regular updates about the Human Traces WG and its activities sign up to the mailing list (listserv.unibe.ch/mailman/listinfo/human-traces.pages).


**Figure 1:** Human Traces in Latin America identified in different biogeographical areas: Mesoamerica (yellow circle) including México and Central America; the Andes (gray circle) including the western part of Ecuador, Peru, Argentina, and Chile; the Pampas (red circle) including Central Argentina and Uruguay; Patagonia (blue circle) including southern Argentina and Chile; and Amazonia (purple circle) including most of Brazil, and part of Colombia, Venezuela, Peru and Bolivia. The time intervals of interest for the Human Traces WG are: Precolumbian (before 1500 CE), European colonization (between 1500 and 1900 CE) and modern times (1900 CE up to present).

AFFILIATIONS
[1]Department of Geography and Planning, University of Liverpool, UK
[2]CONICET, Bariloche, Argentina
[3]Départements de biologie et de géographie, Université Laval, Québec, Canada
[4]Department of Surface Waters Research and Management, Eawag, Dübendorf, Switzerland

CONTACT
Madeleine Moyle: m.moyle@liv.ac.uk

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# International Association of Limnogeologists - International Paleolimnology Association joint meeting: Lagos, Memorias del Territorio

Julieta Massaferro[1], E. Piovano[2], S. Stutz[3] and M. Tonello[3]

**San Carlos de Bariloche, Argentina, 27 November–2 December 2022**

The event was organized in collaboration with the International Association of Limnogeologists (IAL) and the International Paleolimnology Association (IPA). The conference was attended by almost 300 people from 31 countries, including seven in South America.

The goal of the IAL–IPA 2022 conference (pastglobalchanges.org/calendar/27009) was to gather research on lake systems from multiple perspectives, with a focus on both the sediment record from the Earth system archive and the social and cultural memory of the territory. The conference aimed to bridge the gap between a broad range of disciplines that work within the overarching theme of Earth system and climate–environment–cultural changes.

The conference was made up of oral and poster presentations about diverse scientific themes and aspects. The general and focus sessions addressed topics such as human traces in the aquatic sedimentary record, the sensitivity of high-altitude aquatic ecosystems, lake biodiversity changes through time and space, and paleoenvironment and paleoclimate records from long-lived lakes. Novel approaches such as molecular application and perspectives on environmental systems, and integration of process models into paleolimnological methods, were topics particularly well received by the audience, especially by young scientists starting out in their careers in paleoscience. Additionally, the program included special sessions about the value of outreach, education, equality, diversity, and inclusion in the field of lake studies, and on the challenge of communicating science to the public.

Every day, invited keynote speakers from the Earth, Biological and Social Sciences presented a wide variety of topics in plenary sessions. Plenary talks were gender balanced, including two female researchers from Chile (Ana Abarzúa, Universidad Austral de Chile) and Argentina (Beatriz Modenutti, Universidad Nacional del Comahue). Esteban Castro, an Argentinean specialist in the field of social sciences, also attended the meeting and spoke about the serious problem caused by human failures behind the devastating water-related risks, threats and disasters suffered worldwide in recent years, and the expected worsening of this situation in many areas of the world.

Pre-conference virtual short courses were organized for students and early-career researchers (ECRs): "The Neotoma Paleoecology Database: How to Access, Use and Contribute Data" (Joy Hobbs, Don Charles and team), "An Introduction to GIS" (Julio Lancelotti) and "Multivariate Statistics for Paleoenvironmental Sciences" (Alex Correa-Metrio). Mid-conference social activities, including a workshop on landscape illustration, walking tours, and a local beer experience fostered a friendly atmosphere for participants. Two different one-day excursions took place on 2 December. During the meeting, Professor Daniel Ariztegui from the University of Geneva was awarded with the IAL W.H. Bradley Medal, which is given to a limnogeologist who is outstanding in their field. The IPA Rick Battarbee Lifetime Achievement Awards were given to Mark Brenner, Steve Juggins, Anson Mackay, Nora Maidana, and John Smol.

The congress was closed by a general IAL-IPA assembly, followed by a gala dinner. The next IAL-IPA Conference, as announced in the general assembly, will be held in 2025 in Savoy, France.

Finally, we would like to thank PAGES for encouraging the participation of ECRs by providing financial support to almost 50 young scientists from different parts of the world.

AFFILIATIONS
[1]CENAC-CONICET, Bariloche, Argentina
[2]CICTERRA-CONICET, Cordoba, Argentina
[3]Universidad de Mar del Plata-CONICET, Mar del Plata, Argentina

CONTACT
J. Massaferro: jmassaferro@comahue-conicet.gob.ar


**Figure 1:**. IAL-IPA 2022 conference logo.

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# Ice Core Science at the three Poles

Hubertus Fischer[1,2] and Margit Schwikowski[2,3]

## International Partnerships in Ice Cores Science (IPICS) 3rd Open Science Conference & Ice Core Young Scientist (ICYS) meeting, Crans-Montana, Switzerland, 2–7 October 2022

The summer of 2022 will enter the climate change history books (again) as one of the hottest on historical record. In particular, southern Europe suffered from extreme drought and wildfires, and central European glaciers experienced the largest annual ice loss since glacier monitoring started. Even the highest areas in the European Alps, such as the Colle Gnifetti, a firn saddle in the Monte Rosa massif on the border between Italy and Switzerland at an altitude of 4500 masl, experienced snow surface temperatures at the melting point. While this news is, per se, already bad enough, it is even more devastating because the Colle Gnifetti site is also known as one of the most famous high-alpine ice-core drilling sites. At this site, Hans Oeschger – a famous climate scientist based in Bern, Switzerland, best known for reconstructing carbon dioxide concentrations using Antarctic ice cores – also initiated a high-alpine ice-core drilling project in the 1970s. The increasing temperatures and summer melt in high-altitude regions, such as the Colle Gnifetti, not only illustrate the anthropogenic warming, but also put an expiry date on the climate archive of high-alpine glaciers.

With this background, the international ice-core science community assembled for its third Open Science Conference (OSC) (pastglobalchanges.org/calendar/26967) in Crans-Montana, a ski resort above the Rhone Valley in Switzerland, only about 50 km from the Colle Gnifetti. The OSC brought together ice-core scientists from 20 countries working on the Greenland and Antarctic ice sheets as well as high-altitude glaciers; hence the theme of the conference was chosen to be "Ice Core Science at the three Poles." Also, a few intrepid specialists from other paleoclimate science areas attended the conference. The conference had been initially planned for 2020 but was postponed twice due to the COVID-19 pandemic. It could finally take place in fall 2022, allowing scientists from all regions of the globe to attend.

Of course, the authors of this report, who were also the conference chairs, are biased, but it was worth the wait! With 270 participants on site, and about 20 joining online, it was the largest IPICS OSC ever, and spirits were extremely high, showing that ice-core science is thriving and more important than ever. Latest proxy developments in ice-core science and from other areas of paleoclimate research, new ice-core drilling techniques, new high-resolution ice-core records, and reports from, and plans for new ice-core projects (ranging from rescuing high-altitude glacier archives to securing the oldest ice on Earth) were presented in lectures from invited speakers, science talks and several poster sessions, with a high number of contributions. Moreover, the OSC was preceded by the traditional young scientist meeting organized by the ice-core early-career network ICYS, and attended by more than 130 early-career scientists. This meeting offered insights into additional aspects of research today, and instructed the attendees in various facets of science communication and research career development.

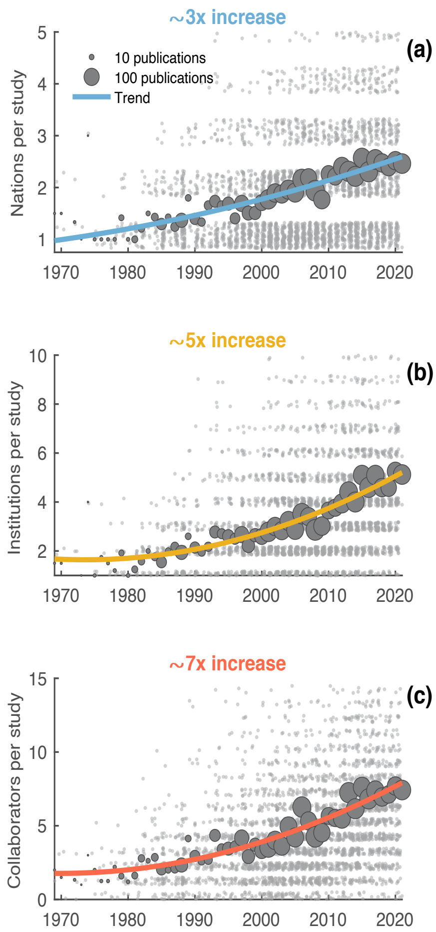


**Figure 1:** Results of a publication analysis (3423 papers included) on the evolution of ice-core science over the last five decades and the potential impact of the foundation of IPICS (after an NSF-funded workshop in Virginia in 2004) on international collaborations within the field of ice-core sciences (from Osman et al. 2022). Small gray dots refer to individual publications, larger dots to the annual average, where the size of the dots is scaled by the number of publications per year.

Certainly, the perfect organization by conference manager Doris Bühler from the Paul Scherrer Institute, the warm welcome and support by the conference center, Le Régent, and the typical Swiss hospitality, with both light and cheesy food, kept spirits and energy levels high for the entire week. Hands-on experience in glacier loss was provided by an excursion to the Great Aletsch Glacier on Wednesday afternoon, while a highlight was certainly the transdisciplinary theater production (initiated by Margit Schwikowski and author and theatre director Sabine Harbeke) called "Fleeting ice - news of tomorrow" (fluechtigeseis.ch) which took place on Tuesday evening. This theater performance illustrated the waning of ice due to climate change in sounds, enactment, and music, and was acknowledged by the IPICS scientists with standing ovations. A post-conference excursion to the Research Station Gornergrat at the foot of the Colle Gnifetti completed the program.

Of course, all this would not have been possible without a large number of sponsors (indico.psi.ch/event/6697/); PAGES was one of them, providing generous support for young researchers from low- to middle-income countries. Given the success of the conference and the outstanding contributions by many early-career scientists, ice-core science itself does not seem to be at risk (see also Fig. 1). We look forward to the next IPICS OSC to be held in 2026!

AFFILIATIONS

[1]Climate and Environmental Physics, Physics Institute, University of Bern, Switzerland

[2]Oeschger Centre for Climate Change Research, University of Bern, Switzerland

[3]Paul Scherrer Institute, Villigen, Switzerland

CONTACT

Hubertus Fischer: hubertus.fischer@unibe.ch

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# Interglacials of the 41 kyr-world and the Middle Pleistocene Transition

Sophia K. Hines[1], S. Shackleton[2] and C. Tzedakis[3]

**QUIGS workshop, Palisades, NY, USA, 19–21 September 2022**

Understanding the evolution of Quaternary glacial cycles has been a long-standing question in paleoclimate science. In the Early Pleistocene, glacial cycles appear symmetric with smaller ice volumes and a period of 41 kyr. Over the course of the Middle Pleistocene Transition (MPT; ~1.25–0.65 Myr BP), glacial cycles became longer (~100 kyr), stronger, and more "saw-tooth" shaped (Fig. 1a). The workshop aimed to examine differences between interglacials of the 41-kyr and 100-kyr worlds and assess hypotheses for the MPT. The meeting, held at Lamont-Doherty Earth Observatory of Columbia University, was the third meeting of QUIGS (pastglobalchanges.org/quigs) Phase 2, attended by 49 participants (27 in person, 22 online) from 11 countries, including 17 early-career researchers (ECRs).

### Structure and duration of the 41-kyr world interglacials

The traditional view of the 41-kyr world is that ice-volume changes reflect a more linear response to obliquity forcing, often producing interglacial shapes resembling isosceles triangles. This was challenged by the emergence of new high-resolution records from the Iberian Margin (David Hodell, Joan Grimalt, Chronis Tzedakis), revealing a variety of shapes, durations, and intensities. Modeling by David Hodell, and by Yasuto Watanabe and Ayako Abe-Ouchi, showed that the phasing of precession and obliquity influences the structure and duration of interglacials of the 41-kyr world, as well as the timing of glacial terminations and inceptions. Discussions underscored the importance of comparing ice-sheet model results with glacial-geologic data to improve our understanding of the structure of 41-kyr cycles.

### Basic questions remain about the MPT

The second focus of the meeting centered on our understanding of the driver(s) of the MPT. Presentations considered whether the MPT was caused by shorter- or longer-term changes, or whether the transition resulted from a threshold response in the ocean-atmosphere system to a more gradual forcing. Hypotheses included: 1) Regolith removal by land ice that changed ice-sheet dynamics and led to the emergence of larger ice sheets; the larger ice sheets, in turn, led to the skipping of insolation cycles and the appearance of ~100-kyr glacial cycles (Clark and Pollard 1998); 2) Long-term cooling that led to a gradual rise in the insolation threshold required for deglaciation and, in turn, to an increase of skipped obliquity cycles; the emergence of longer glacials then allowed the accumulation of larger ice sheets (Tzedakis et al. 2017); 3) The combined effect of long-term cooling driven by $CO_2$ drawdown and regolith removal (Willeit et al. 2019); 4) Antarctic ice-sheet growth (from land-based to marine-based margins), which changed the structure of deep ocean circulation and carbon storage; the resulting atmospheric $CO_2$ drawdown led to the increase in Northern Hemisphere ice sheets and the 100-kyr cycle (e.g. Farmer et al. 2019; Ford and Raymo 2020; Peña and Goldstein 2014); 5) Strengthening Atlantic Inflow into the Nordic Seas enhanced poleward moisture transport and promoted the growth of larger ice sheets which spread southwards and resulted in a shift from ~41 to ~100 kyr cyclicity (Barker et al. 2021). However, the ultimate trigger for many of these hypotheses remains elusive (Fig. 1b).

The discussions highlighted the need for more proxy and atmospheric greenhouse gas data, but also a critical evaluation of existing proxies and records. For instance, Peter Clark challenged the interpretation of benthic $\delta^{18}O$ as primarily indicating a change in ice volume across the MPT and suggested that much of the $\delta^{18}O$ change across the MPT was driven by ocean cooling. Sophie Hines challenged the traditional interpretation of εNd as predominantly indicating changes in water mass geometry (and thus deep-ocean circulation). Using new high-resolution εNd data from the Cape Basin, she suggested a more nuanced interpretation of εNd that reflects both changes in deep-ocean circulation and endmember composition across the MPT. Reconciling records using various tracers of deep-ocean circulation (particularly $\delta^{13}C$ and εNd) will help narrow the range of MPT hypotheses.

The next QUIGS workshop ("Interglacial Intensity") will take place in Grenoble, France, in September 2023 (pastglobalchanges.org/calendar/137088).


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We thank all the participants who engaged in this workshop, and PAGES and the LDEO Climate Center for their support.



AFFILIATIONS

[1]Marine Chemistry & Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, USA

[2]Department of Geosciences, Princeton University, USA

[3]Environmental Change Research Centre, Department of Geography, University College London, UK

CONTACT

Chronis Tzedakis: p.c.tzedakis@ucl.ac.uk



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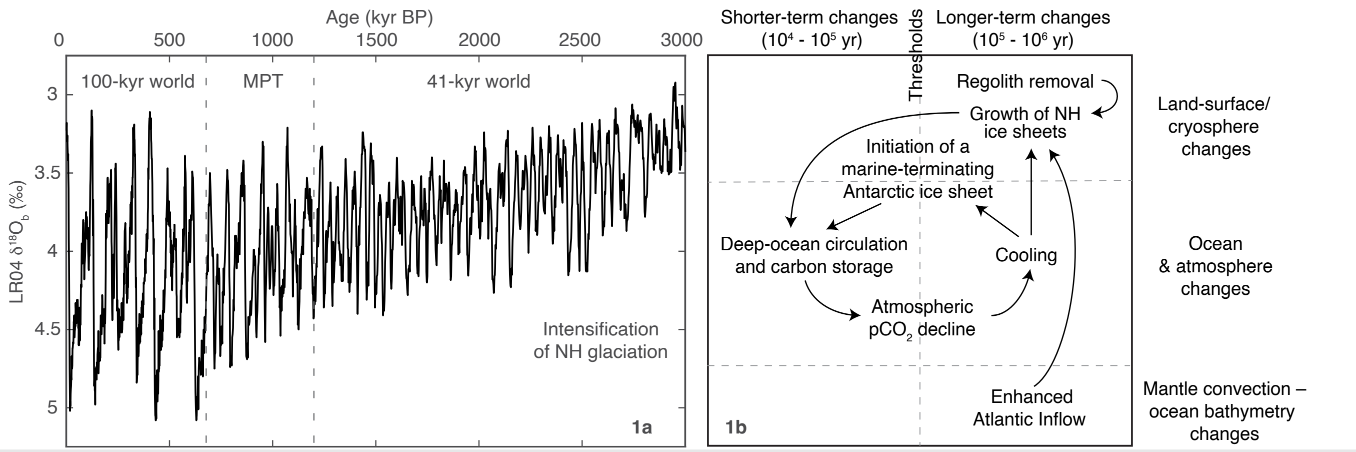


**Figure 1: (A)** LR04 benthic $\delta^{18}O$ stack (Lisiecki and Raymo 2005), showing the evolution of glacial cycles over the last 3 Myr. **(B)** Schematic of the types of drivers and changes invoked in different MPT hypotheses.

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# Early-career researchers embrace interdisciplinary paleosciences: The joint PAGES–INQUA workshop

PASES workshop organizers*

**La Serena, Chile, 20–24 November 2022**

The workshop on Past Socio-Environmental Systems (PASES) took place in La Serena, Chile (pastglobalchanges.org/calendar/26972) and was organized by the early-career networks of PAGES (Past Global Changes) and INQUA (International Union for Quaternary Science).

The aim of the workshop was to provide a common platform for early-career researchers (ECRs) working on past climate-environment-cultural changes. The scientific essence of the meeting was to offer the opportunity to discuss different proxies and perspectives, as reflected by the titles of the presented talks (Fig. 1). An interdisciplinary approach is necessary for understanding socio-environmental systems: the complexity of the causal relations between the natural and human-driven forcings can be grasped by acquiring data and methods from different disciplines and interpreting them using a multiple working hypotheses framework.

The workshop was held after a two-year postponement due to the COVID-19 pandemic, with the participation of 20 ECRs and four keynote speakers from 10 different countries from four continents. The meeting was held at the Archaeological Museum of La Serena, and coordinated by the Center for Advanced Studies in Arid Zones (CEAZA). The workshop consisted of three days of oral presentations, and included breakout activities, outreach talks involving high-school students and local communities, and a one-day field excursion.

Presentations were organized into three thematic sessions which provided scientific foci. The session on "Novel techniques in past human-environmental couplings" tackled recent advances in methods and proxies from sedimentary sequences for improving our understanding of human impacts on ecosystems. These methods range from functional approaches of biological proxies and biomarkers, to archaeological heritage conservation. During the session on "Socio-Environmental Systems in the Anthropocene", researchers presented provocative talks, such as the social component of the term "Anthropocene", and socio-economic responses to climate change in past archaeological societies. Finally, the "Synthesizing archaeological, paleoclimatic and paleoecological records" session presented a wide range of practical ways to integrate diverse records. These included paleo-monsoon dynamics and links with socio-cultural changes in India, and Late Quaternary extinction of megafauna in South America. Talks also revealed the importance of numerical approaches widely used across disciplines (e.g. machine learning, species distribution models) to decipher the dynamics of human-environmental relationships.

During the breakout activities, participants were divided into three groups to discuss the overarching topic of resilience of past climate-environment-cultural systems. As part of the original PASES registration process, we asked interested people to list the most urgent questions related to the workshop topic. Over 150 questions were proposed at that stage, and a few of them were selected as the starting point for group discussions in La Serena. The questions revolved around types of proxies and archives, semantic barriers, and analytical frameworks in past socio-environmental systems.

The rich cultural heritage of the PASES venue, the Coquimbo region, was visited during the mid-workshop excursion. Participants learned from an enthusiastic team of local guides how and when humans interacted with the environment during historical times. The visit also included an exploration of archaeological landmarks of the Guanaqueros city. Led by Dr. Carola Flores, associate researcher at CEAZA and PASES keynote speaker, participants walked through the Valle de el Encanto and got to know its cultural heritage, characterized by enigmatic rock art and its "piedra tacitas" (human-carved rocks, of which the origins and function are still debated).

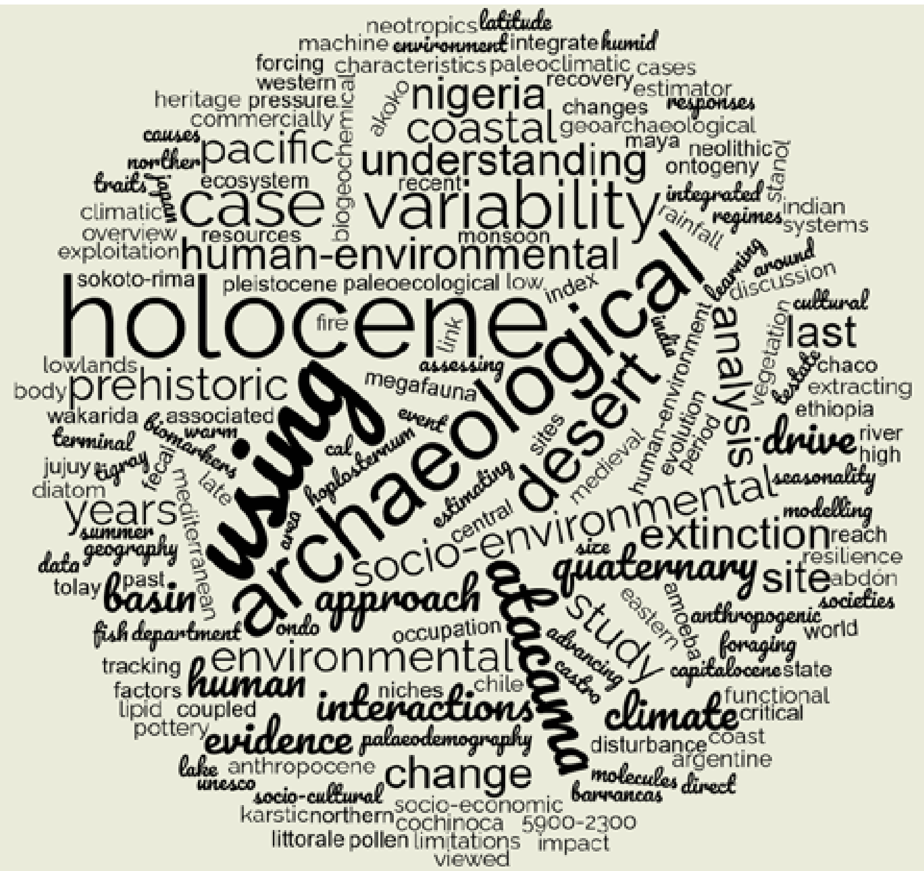


**Figure 1:** The diverse range of topics from the presentation titles at the PASES workshop represented in a word cloud.

## Summary and ways forward

Organizing the PASES workshop has been both challenging and rewarding, and has allowed us to build a network for long-term collaborations. Outputs of the breakout activities, and lessons learned during the workshop planning and organization, were incorporated into this *Past Global Changes Magazine* special issue (p. 38-39).

AFFILIATIONS
*See the online version for the complete author list

CONTACT
Xavier Benito: xavier.benito.granell@gmail.com

 

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# News from paleoscience data organizations

Darrell Kaufman[1] and Lukas Jonkers[2]

A major outcome for many PAGES Working Groups (WGs) (pastglobalchanges.org/science/current-wg) is their data-intensive synthesis product featuring a high level of data stewardship. These follow the long tradition in the paleoscience community of sharing and caring for the community's data resources. PAGES WGs and the broader paleoscience community are fortunate in these efforts for the support of numerous discipline-specific data repositories and organizations. Their services help assure that our data are FAIR – findable, accessible, interoperable, and reusable (go-fair.org/fair-principles). We asked five international paleo data organizations to tell us about their latest activities of interest to the PAGES community.

### PANGAEA

PANGAEA (Data Publisher for Earth & Environmental Sciences) (pangaea.de) is an open-access library for archiving, publishing, and disseminating georeferenced data from the Earth, environmental, and biodiversity sciences. It is operated jointly by the German research institutions MARUM in Bremen and AWI in Bremerhaven. Grown from its origins as a paleoclimate archive, PANGAEA now hosts >400000 datasets with more than 24 billion datapoints. Each dataset includes a data citation and a unique Digital Object Identifier (DOI). To add additional value to the archived datasets, PANGAEA now offers data-usage statistics where the number of web-based interactions with each dataset are tracked, and the impact of data sharing can be measured.

### LinkedEarth

LinkedEarth (linked.earth) advances paleoclimate data standards and research. Datasets tied to LinkedEarth projects typically employ the Linked PaleoData (LiPD) structure. To improve searching across the breadth of LiPD datasets, the vocabulary for seven key paleoclimate variables has now been standardized on lipdverse.org, while aligning them to NOAA's PaST Thesaurus (ncei.noaa.gov/products/paleoclimatology/paleoenvironmental-standard-terms-thesaurus). The open-source code ecosystem around LiPD is expanding, most notably with geoChronR (McKay et al. 2021), actR (github.com/LinkedEarth/actR) and Pyleoclim (Khider et al. 2022); new LiPD utilities in Python and analytical tools in R are forthcoming. Online workshops are training paleoscientists to use this budding research ecosystem, and an advanced in-person workshop will take place during summer 2023 in California, USA.

### EuroClimHist

EuroClimHist (euroclimhist.unibe.ch/en) is a database of historical climate data based on documentary and early instrumental evidence augmented by proxy records from natural archives. It is operated by the Institute of History, Department of Social Economic and Environmental History, and the Oeschger Centre for Climate Change Research at the University of Bern, Switzerland. The volume of data that is publicly accessible has recently increased. Two larger bodies of Swiss weather observations, including large phenological data on a nearly daily basis, have been included (Rudolf Salis-Marschlins, 1781–1800; Jakob Hänni 1839–1870). In collaboration with the World Glacier Monitoring Service (WGMS), a large number of historical paintings, drawings and early photographs of Swiss glaciers have recently been entered into the database. An upcoming project will focus on glaciers from the western Alps and Norway.

### World Data Service for Paleoclimatology

The World Data Service for Paleoclimatology (ncei.noaa.gov/products/paleoclimatology), hosted by National Oceanic and Atmospheric Administration (NOAA), has now completed minting new DOIs for the backlog of >10 000 individual datasets that have been contributed over the past three decades. The NOAA Paleoclimatology now routinely assigns DOIs to new contributions. The DOIs are available on each landing page and in metadata files (see this example landing page). Instructions for new submissions, along with requirements and timelines for obtaining a dataset DOI, are being updated and will be announced via the Paleoclimate List when available. Dataset DOIs are important to cite along with publications to give full credit to data generators.

### Neotoma

The Neotoma Paleoecology Database (neotomadb.org) features an improved website with access to 31,900 datasets, comprising 10.7 million datapoints from 19,100 sites. Neotoma is working closely with LinkedEarth to build import–export capabilities with the popular LiPD format. Data mobilization campaigns for fossil pollen data are underway, particularly in Africa, the Indo-Pacific, and Latin America. ª new NSF-funded project is enhancing Neotoma support for both FAIR and CARE (Collective benefit, Authority to control, Responsibility and Ethics) data standards, in partnership with other paleodata resources. A new project is developing controlled vocabulary for lipid biomarker variables, with support from Belmont Forum, and another is partnering with a coalition of labs to support the curation of sedimentary (ancient) DNA datasets. Online and in-person educational workshops are planned, including at INQUA2023.

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AFFILIATIONS

[1]School of Earth and Sustainability, Northern Arizona University, Flagstaff, USA

[2]MARUM Center for Marine Environmental Sciences, University of Bremen, Germany

CONTACT

Darrell Kaufman: Darrell.Kaufman@nau.edu

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**Figure 1:** The paleoscience community is fortunate to be supported by discipline-specific data repositories and organizations which help assure that our data are FAIR – findable, accessible, interoperable, and reusable.

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# The Peatland Paleo Proxy Database

Nicole Sanderson[1,2], J. Loisel[1] and A. Gallego-Sala[3]

**The PAGES Data Stewardship Scholarship program allowed us to organize and archive multiple published peat-based paleoecological datasets, increasing their accesibility and visiblity via cross-platform linking.**

For many years now, the C-PEAT working group (pastglobalchanges.org/c-peat) has made available hundreds of peatland-carbon datasets. So far, these datasets only include limited information, namely age-depth model and peat geochemical data (bulk density, carbon and nitrogen content, etc.). But there is a wealth of peat-based paleo-proxy data that remains sparse in public repositories. The PAGES Data Stewardship Scholarship has allowed us to build a framework to organize and archive our community's peat-based paleoecological datasets. We are also integrating this dataset to the Neotoma database (neotomadb.org). The interest has been high among the peat community to see peat records further integrated to regional paleoclimate reconstructions, such as the 2k Network (pastglobalchanges.org/2k). Increasing the accessibility and visibility of peat-core paleoproxy data should help to fulfill this goal. We hope we can convince paleoclimatologists working with lake sediments, speleothems, tree rings, ice cores, and other archives of peat's promise!

## Peatland archives

Peatlands are arguably the very first recognized paleoclimate archives. In the 19th century, the alternating dark and light layers from European peat deposits were interpreted as indications of warmer/drier and wetter/cooler conditions, respectively (Blytt 1876). These records of past climate change, which were based on plant macrofossils and pollen assemblages, led to the development of the first deglacial paleoclimate sequence: the Blytt-Sernander classification (Blytt 1876; Sernander 1908). Today, with thousands of peat profiles described and analyzed from every continent, peat-based paleoclimate work remains an active field of research.

Despite this long history and the large number of published studies, peat-based paleorecords remain somewhat underutilized. They are also seldom combined with those from other terrestrial archives, such as lakes, trees, and ice. Here we contend that peatland archives can offer complementary insights in Holocene paleoclimatology due to: (1) their global distribution, including regions where other terrestrial archives are rare; (2) their temporal coverage and resolution, which can offer decadal-scale Holocene reconstructions; and (3) their capacity to record changes in temperature, moisture source, or other climate components.

## Data aggregation and formatting

Over the past two years, C-PEAT Data Steward Nicole Sanderson has gathered as many peat-based paleoecological datasets as possible. She led a number of "peat proxy happy hour" sessions to engage with data owners and facilitate data transfer. She trained a couple of undergraduate researchers (Kendahl Hejl and Daniel Maraldo) in data formatting and quality control. She became a Neotoma data steward and has been actively discussing the Peatland dataset with Neotoma leaders. These efforts have paid off: 182 chronologically constrained paleorecords from 101 cores have recently been processed by our team (Fig. 1). Those cores are globally distributed, though most of them are located in the Northern Hemisphere. The dataset includes chronologically constrained testate amoebae, plant macrofossil, and geochemical records, as well as novel proxies such as biomarkers and stable isotopes (Fig. 1). Prior to our work, Neotoma only contained 18 peat-based paleorecords. The newly formatted records are being integrated on Neotoma and should be available sometime this year.

## Current and future plans

The Peatland Paleo Proxy Database will be available for community use on Neotoma, and we aim to continue to expand its contents in order to improve process-based models. This new C-PEAT database will be used to assess ecosystem responses to past environmental drivers, including recovery from past abrupt changes in water table depth and temperature, as well as building carbon trajectories. We also aim to integrate the peat-based paleorecords with other terrestrial records (e.g. lake sediments, tree rings) in regional paleoclimate reconstructions. Our team is preparing a manuscript that describes the proxies included in the dataset and the methods used to format, synthesize, and analyze the paleo peatland records. Ultimately, we aim to link this dataset through LiPD (lipd.net).

ACKNOWLEDGEMENTS

We would like to thank Kendahl Hejl and Daniel Maraldo for their help building the database; Socorro Dominguez Vidana and Simon Goring for their technical support through Neotoma; the C-PEAT community for sharing their datasets and knowledge.

AFFILIATIONS

[1]Department of Geography, Texas A&M University, College Station, USA

[2]Department of Geography, University of Quebec in Montreal, Canada

[3]Department of Geography, University of Exeter, UK

CONTACT

Julie Loisel: juloisel@hotmail.com

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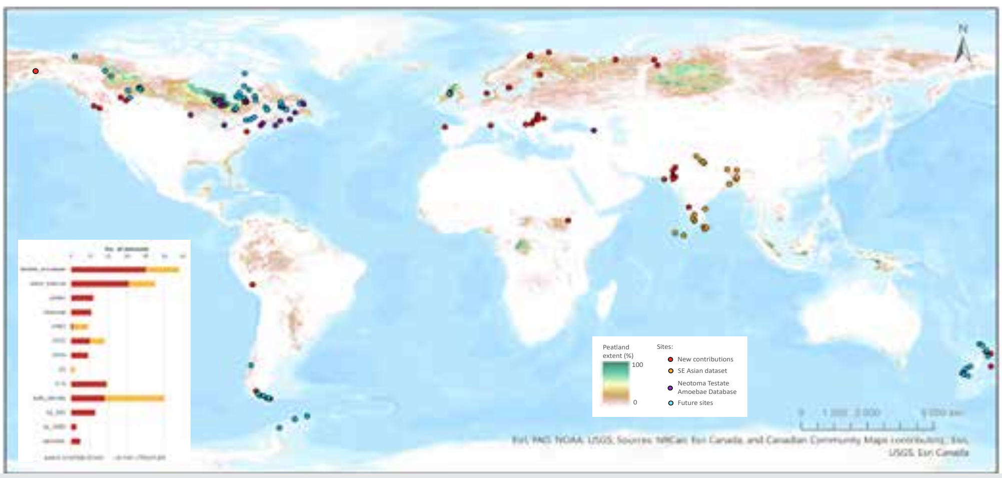


**Figure 1:** The Peatland Paleo Proxy Database as of 31 December 2022. It comprises 182 records from 101 cores. Orange = Neotoma Testate Amoebae Database; red = new proxy data contributions; blue = metadata only (for now). Modified from Melton et al. (2021).

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# Advancing Last Interglacial and Holocene sea-level databases

Alessio Rovere[1,2], J.S. Garzón[3], J.M. Doherty[4] and N. Khan[5]

**The PAGES Data Stewardship Scholarship program contributed to the development of an online database interface and a visualization tool of past sea level by the PALSEA working group.**

The creation of reporting standards for sea-level proxies and the compilation of sea-level databases have been a central focus of the PALeo constraints on SEA level rise (PALSEA) working group (pastglobalchanges.org/palsea) since its inception (Düsterhus et al. 2016; Rovere and Dutton 2021). Over the last three years, these efforts came to fruition with two products. First, a global database of post-Last Glacial Maximum (LGM) sea-level index points was created within the Geographical variability of Holocene sea level (HOLSEA) project (Khan et al. 2019). Second, the creation of the World Atlas of Last Interglacial Shorelines (WALIS; Rovere et al. 2022) database, which includes sea-level proxies dating back to Marine Isotopic Stage (MIS) 5.

With the completion of these two databases, ideas started to arise concerning the feasibility of uniting them under a single interface and the availability of visualization and interfaces to allow for their exploration, and facilitate data query and download. With these ideas in mind, we submitted a proposal for a Data Stewardship Scholarship to PAGES. The proposal had two primary goals. The first was to implement the Holocene sea-level data standard format (Khan et al. 2019) into the interface built for the WALIS database (available here: alerovere.github.io/WALIS), eventually duplicating the database done within the HOLSEA project into WALIS. The second goal was to provide a visualization interface for the WALIS data, taking inspiration from the one already proposed for the HOLSEA database (Drechsel et al. 2021).

The first result of our work was the implementation of the HOLSEA data template into the WALIS database structure, including the online database interface. This work is now complete. As a result, any user logging into the WALIS online data insertion interface will not only be able to insert MIS 5 data, but will also find a series of tabs dedicated to the insertion of standardized Holocene data, including tables for radiocarbon, U-series, archaeological, and other age attribution methods. The Holocene part of the WALIS interface is currently undergoing beta testing, but is fully functional. After this phase, we plan to release a non-beta version of the interface, populated with the post-LGM data already in the HOLSEA database.

The second achievement of our work was the creation of a platform to query and analyze the data already included in WALIS. This work was done through an R Shiny App querying a simplified version of the WALIS database (i.e. including only the essential fields related to indicator type, paleo sea level and dating information). The app is currently in its 2.0 version. The code to run the app offline is available from Garzón and Rovere (2022), and the app is also accessible online at this link: warm-coasts.shinyapps.io/WALIS_Visualization/. The application is divided into three pages, which the user can navigate. On the first page, it is possible to filter the data by geographic selection, age, elevation, or indicator type. On the second page, the app allows the previously selected data to be downloaded in .csv format. Finally, on the third page, the app allows further fine-tuning of the data query by excluding specific index points and calculating an age/sea-level probability density graph using a Monte Carlo approach.

The results briefly described above represent a fundamental stepping stone towards increasing the wide availability and usability of paleo sea-level data. Our data and code are fully open access. Bug reports and suggestions on how to improve the current products and forks to the GitHub repositories linked to the published code versions are also welcome.


## ACKNOWLEDGEMENTS

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## AFFILIATIONS

[1]Department for Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, Italy
[2]MARUM, Center for Marine Environmental Sciences, University of Bremen, Germany
[3]Laboratory of Geo-information Science and Remote Sensing, Wageningen University & Research, The Netherlands
[4]Environmental Law Institute, Washington DC, USA
[5]Department of Earth Science, The University of Hong Kong, Hong Kong

## CONTACT

Alessio Rovere: alessio.rovere@unive.it


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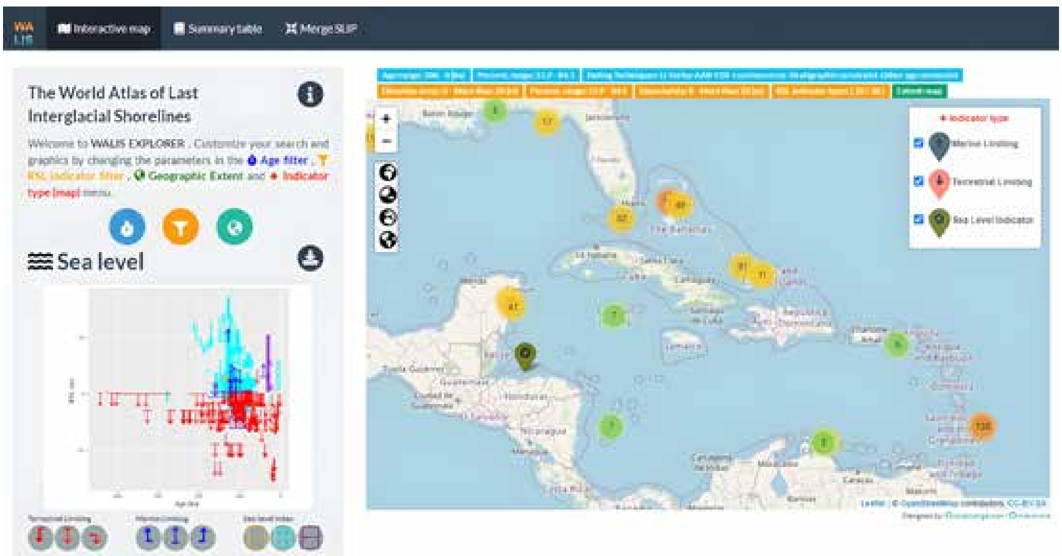


**Figure 1:** A screenshot of the WALIS Data Explorer application.

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**PAGES International Project Office**
Hochschulstrasse 4
CH-3012 Bern
Switzerland

**Telephone** +41 31 684 56 11
**Email** pages@pages.unibe.ch
**Website** pastglobalchanges.org
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