VOLUME 30 · NO 1 · APRIL 2022

PAST GLOBAL CHANGES
MAGAZINE

USING PALEOECOLOGY IN RESTORATION ECOLOGY

EDITORS
Lindsey Gillson, Cathy Whitlock, Peter Gell, Sabine Prader, Willy Tinner and Sarah Eggleston

SPECIAL SECTION
Socio-ecological approaches to conservation

EDITORS
Daniele Colombaroli and Evan Larson

PAGES

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News

Working group news
Two new working groups launched at the beginning of 2022:
PlioMioVAR (Pliocene and Miocene climate variability over glacial-interglacial timescales) builds on key priorities identified by the community in the PAGES PlioVAR working group.
pastglobalchanges.org/pliomiovar

Q-MARE (Disentangling climate and pre-industrial human impacts on marine ecosystems) aims to produce new results on biodiversity loss under natural climate variability and sustainability of both ecosystems and societies.
pastglobalchanges.org/q-mare

Sir Nicholas Shackleton Medal For Outstanding Young Quaternary Scientists Award 2021
Congratulations to Dr. Julie Loisel, co-leader of the PAGES C-PEAT working group, on being named the 2021 recipient of the Sir Nicholas Shackleton Medal For Outstanding Young Quaternary Scientists Award.

PAGES webinars
In December 2021, PAGES organized its 6th and 7th webinars. The PAGES-WCRP webinar introduced the new WCRP, its new science foci, and its elements, and highlighted interfaces across which enhanced interactions and collaborations with PAGES can flourish in the future. The PAGES-PMIP webinar aimed to help people find and use data from the PMIP simulations that could be useful for their own research, introduced which climate models and periods have been used in PMIP, and dsicussed all things data related.
youtube.com/playlist?list=PLSaCdvmD4wMIlbBmw5tulJc5cpmoxYbER

PAGES Early-Career Network (ECN)
A new community-driven ECR project (and product of the joint PAGES-INQUA early-career workshop 20-24 November in La Serena, Chile) on synthesizing human–climate–environment interactions has been launched. The project is entitled "The whole is not the sum of the parts: building a synthesis database of past human-environmental systems in the Global South (pSESYNTH)" and aims to test a key hypothesis, i.e. whether or not cultural "stress" of ecosystems was widespread across the Global South during the Holocene. Visit the website for more information and to sign up.
pases2020.com/index.php/psesynth-project

PAGES mobility fellowships
As part of an effort to actively promote the participation of early-career scientists and scientists from low- and middle-income countries in relevant working groups, workshops, and other activities, PAGES launched two mobility fellowships in 2021. The first awardees of the Inter-Africa Mobility Research Fellowship Program and the IAI International Mobility Research Fellowship Program for Latin America and the Caribbean can be viewed on the PAGES website. The next deadline for all applications is 19 August. Check our website for more information and updates: pastglobalchanges.org/support

PAGES IPO staff update
PAGES International Project Office welcomed Leigh Martens Winiger in November 2021. Leigh will be sharing the communications and project tasks with Chené van Rensburg. The IPO also welcomes Dr. Basil Davis who will be joining the team for a period of six months. Contact details for all IPO staff are available here: pastglobalchanges.org/about/structure/international-project-office

Deadline for new working groups, phase extensions, and workshop support
The next deadline to propose a new PAGES working group, apply for a working group phase extension, submit an application for the data stewardship scholarship, or apply for financial support for a workshop/meeting or conference is 19 September. All details: pastglobalchanges.org/support

***Past Global Changes Magazine*: Changes to distribution**
PAGES is happy to be able to offer free online access to *Past Global Changes Magazine*, as well as free hard copies to all interested parties. As an organization focused on climate and environment, we are also interested in keeping the number of printed copies to a minimum. We are, therefore, in the process of making changes to our distribution strategy. Any changes will be communicated, with ample warning, through our social media channels, website, and e-news. In the meantime, please take a moment to update your profile on our People Database to ensure that the magazines are being sent to the correct postal address: pastglobalchanges.org/people-database. We sincerely hope that this does not cause any inconvenience and thank you for your understanding.

Upcoming issue of *Past Global Changes Magazine*
Our next magazine, guest edited by Matthew Chadwick, Amy Leventer, Anna Pienkowski, and Heike Zimmermann from the C-SIDE and ACME working groups, focuses on sea ice in the polar regions. Although preparations are well underway, if you would like to contribute, please contract our Science Officer: sarah.eggleston@pages.unibe.ch

Calendar

4th PAGES Young Scientists Meeting
9-13 May 2022 – Online

6th PAGES Open Science Meeting
16-20 May 2022 – Online

PALSEA: Palaeo sea level and ice sheets for Earth's future
17-20 July – Singapore

Climate Change, The Karst Record
18-20 July – Innsbruck, Austria

IPICS 3rd Open Science Conference
2-7 October – Crans Montana, Switzerland

pastglobalchanges.org/calendar

Featured publications

ACME
Heikkilä M et al. published an invited review in *Anthropocene* on predicting the future of coastal marine ecosystems in the Arctic and the potential of palaeoenvironmental records.
pastglobalchanges.org/publications/128874

DiverseK
Zhang Y et al. investigate vegetation response to Holocene climate change in Central–East China, and Hawthorne D et al. argue for the use of paleo-ecological records as a guide for fire management in Ireland.
pastglobalchanges.org/taxonomy/term/219/publications

Floods Working Group
Wilhelm B et al. compile paleoflood records to assess the uncertain impact climatic trends might have on flood frequency and magnitude in the European Alps.
pastglobalchanges.org/publications/128890

PALSEA
PALSEA is proud of the list of 32 papers that have been published within the past year. The full list of almost 200 PALSEA peer-reviewed articles, *PAGES Magazine* articles, and special issues can be found on the PALSEA publications website:
pastglobalchanges.org/taxonomy/term/116/publications

VICS
Plunkett G et al. challenge previous assumptions of a volcanic event, highlighting the need to revise the Common Era ice-core chronology and be formally accepted by the wider ice-core and climate modeling communities.
pastglobalchanges.org/publications/128860

Cover

Rapidly changing ecological conditions challenge forest management and restoration, raising questions about how reference conditions are defined and where restoration is warranted, especially as we move towards climatic conditions with no past analog. Two images from the subalpine forest landscapes of the Rocky Mountain National Park, CO, USA, illustrate widespread tree mortality between 2006 (left) and 2021 (right), as a result of spruce bark beetles (foreground) and two unusual wildfires, in 2012 and 2020 (mid- and background), both of which burned in October, well after the historical fire season in the region (photo credit: P. Higuera).

doi.org/10.22498/pages.30.1.3

Mainstreaming paleoecology into ecosystem restoration

Lindsey Gillson[1], C. Whitlock[2], P. Gell[3], S. Prader[1] and W. Tinner[4]

2021 marked the beginning of the United Nations Decade on restoration ecology. Restoration of ecosystems is essential in slowing biodiversity loss and associated erosion of ecosystem services. However, defining restoration goals in an uncertain and changing world raises fundamental questions of what we are restoring and why. The purpose of this special issue is to explore the contributions of paleoecology in addressing these questions and to encourage better integration of paleoecology into restoration ecology and conservation planning.

What are we restoring?

The most obvious–and yet still underutilized–use of paleoecological data in restoration ecology is to provide reference conditions, especially in ecosystems that have experienced significant anthropogenic degradation over periods of time that extend beyond living memory or historical records (e.g. Finlayson and Gell p. 10; Marcisz et al. p. 12; Hapsari et al. p. 14). Paleoecological data sometimes reveal surprises regarding the extent and composition of vegetation in the past, showing that current vegetation is in fact far from natural, and confirming or rejecting the status of alien species (Nogué et al. p. 4; Wilmshurst and Wood p. 26). Although "naturalness" is a contested term, areas with minimal or light human impact are, nevertheless, an important landscape component in many regions (e.g. Nanavati et al. p. 22; Morales-Molino and Schwörer p. 6; Rull p. 18; Finsinger et al. p. 8). Restoration of desired cultural landscapes can also have benefits to both biodiversity and people (see Rull p. 18).

Even without significant human impact, most landscapes are dynamic and respond to multiple interacting environmental drivers, including changes in climate, disturbance, land use, and biotic interactions. Understanding the long-term importance of fire and herbivory, for example, is an important scientific contribution from paleoecology, particularly as it relates to climate extremes, land abandonment, and rewilding (Higuera et al. p. 30; Morales-Molino and Schwörer p. 6). Interactions among environmental, biotic, and anthropogenic drivers can also cause shifts between alternate stable states. This is especially likely at ecotones (vegetational transitions), which are sensitive to subtle changes in climate, fire, and land use and therefore present particular challenges for restoration (Nanavati et al.p. 22; Giesecke et al. p. 24).

Why are we restoring? From static "baselines" to dynamic processes

In today's changing world, no-analog climate conditions are increasingly likely in the coming decades, and a return to "natural" conditions may be impossible or undesirable. As a result, there has been a shift in restoration ecology towards a broader range of conservation objectives that considers the degree of past anthropogenic modification, as well as the desired ecosystem function or condition (Chambers p. 16; Rull p. 18). Considerations include which ecosystems will be most vulnerable to future climate and land-use change and which should be prioritised for restoration and conservation actions (Adeleye et al. p. 28; Higuera et al. p. 30). Paleoecology can also guide efforts to maintain critical ecological functions, such as pollination, by revealing unsuspected past interactions in species whose ranges are currently disjunct (Wilmshurst and Wood p. 26). The integration of paleoecology into an inclusive, process-based approach to restoration ecology is illustrated in Figure 1. Note that as the future is uncertain, the implementation approach needs to be adaptive.

Conclusions and ways forward

The papers in this issue demonstrate a huge and largely untapped synergy between the disciplines of paleoecology and restoration ecology. Ensuring that this potential is realized will require a concerted effort by the paleoecological community in seven main areas:

- Better calibration of paleoecological datasets to increase their usefulness as reference frameworks for conservation planning.
- Wider incorporation of new techniques, such as ancient DNA/sedimentary DNA, to document past changes in biodiversity (e.g. see Wilmshurst and Wood p. 26).
- Communicating paleoecological findings in an applied context, wherever possible, so that the information is accessible and available to the restoration ecology community and beyond.
- Greater integration of paleoecology with other disciplines and knowledge streams, including traditional ecological knowledge (see Gil-Romera et al. p. 20 and the special section in this issue "Socio-ecological approaches to conservation" p. 33).
- Showcasing the relevance of historical perspectives in process-based thinking and modeling efforts that guide adaptive management planning for emerging conditions and societal preferences (e.g. Morales-Molino and Schwörer p. 6).
- Validating dynamic modeling outcomes, for example, by comparing sedimentary proxy data with simulations of ecosystem changes in response to climate change, disturbance, and land use.
- Encouraging managers and policy makers to think on time scales longer than a few decades so that paleoecological information becomes routinely incorporated into landscape conservation planning (e.g. the Ramsar Convention; see Finlayson and Gell p. 10; Hapsari et al. p. 14; Chambers p. 16).

The paleoecological community has a vital challenge ahead: that of seamlessly integrating paleoecology and neo-ecology, thereby enabling the mainstreaming of paleoecology into restoration ecology and biodiversity conservation.

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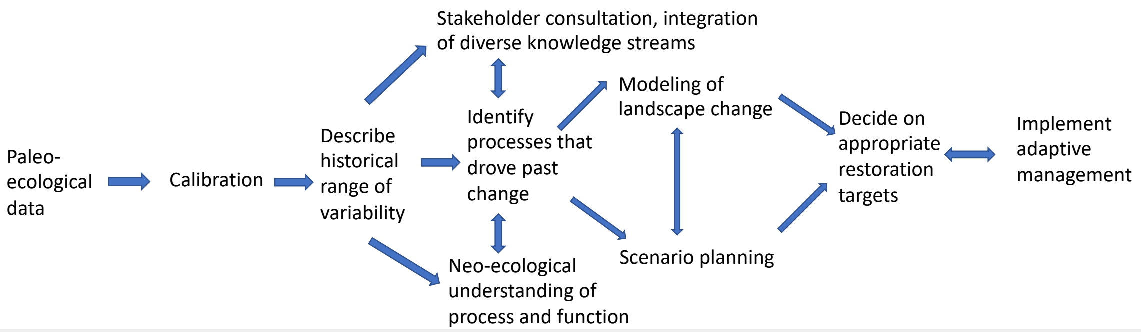

Figure 1: A suggested framework by which paleoecology could be integrated with other disciplines and knowledge streams in a process-based approach to restoration ecology that includes science, modeling, stakeholder consultation and adaptive management.

doi.org/10.22498/pages.30.1.4

Multiple baselines for restoration ecology

Sandra Nogué[1,2], L. de Nascimento[3], W.D. Gosling[4], N.J.D. Loughlin[5], E. Montoya[6] and J.M. Wilmshurst[7,8]

Recent work within restoration ecology has highlighted the importance of incorporating ecological history. Using three complementary examples from New Zealand offshore islands, the tropical Andes, and the Canary Islands, we discuss how restoration goals may be addressed using multiple baselines, or reference conditions, from long-term data.

The idea of using long-term ecological data to measure changes in biodiversity and to improve the effectiveness of conservation strategies has been widely discussed (Willis et al. 2010; Nogué et al. 2017). Importantly, the use of baselines, or reference conditions, has already been recognized in environmental policy such as in the conceptual framework for the 2019 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) global assessment report, and the United Nation decade on ecosystem restoration (2021–2030). It is, therefore, clear that there is now an urgent need to organize and standardize baselines if we want to implement successful restoration actions taking into account the complexity of managing both ecological and cultural systems (Jackson and Hobbs 2009; Nogué et al. 2021). We highlight three case studies to show how restoration goals may be addressed using paleoecologically informed baselines.

(1) Vegetation baselines for New Zealand offshore islands

New Zealand's offshore and outlying islands are important foci for biodiversity protection and conservation, with many supporting species that have been extirpated from the main islands (Bellingham et al. 2010). Most islands have been modified since initial human settlement began ca. 780 years ago, mainly by forest clearance and introduced mammalian pests (particularly rodents, cats, goats and pigs). Conservation efforts in the last 50 years have focused on eradicating alien species and replanting and restoring the "natural" vegetation. However, baselines have usually been informed by historic descriptions of vegetation and/or the composition of nearby forested locations.

Paleoecological records are recognized in New Zealand as an additional tool to document natural pre-human vegetation baselines and to help guide restoration plans (Wilmshurst et al. this issue). Long-term records have also been combined with local Māori (New Zealand's indigenous Polynesian population) knowledge, or *mātauranga*, to provide cultural vegetation baselines and to help inform biocultural approaches to island conservation (Lyver et al. 2015). For example, pollen and charcoal records showed how some forested ecosystems were cleared for Māori gardens, and local Māori communities now desire some forest to be restored to states that would provide a range of future benefits to their cultural, social, economic, and ecological needs (Lyver et al. 2015).

Sometimes paleoecological records can reveal surprises that overturn current ecological understanding. For example, the Poor Knights Islands in northeastern New Zealand are currently covered in a tall forest of native angiosperm trees dominated by *Metrosideros*. This vegetation composition has long been considered to be in a natural baseline state and is used to inform replanting of degraded islands in the region. However, a 2000 year record of pollen, charcoal and ancient plant DNA from a soil core on the island (Fig. 1) tells a different story (Wilmshurst et al. 2014). The forest was cleared by fire in the 13th century and gardened by Māori for ca. 550 years, followed by 180 years of forest succession after they ceased living there. The pre-human vegetation was completely different to today's forest, consisting of a diverse, conifer-dominated forest (e.g. *Dacrydium cupressinum* and *Prumnopitys ferruginea*) with an understory palm (*Rhopalostylis sapida*) and several other locally extinct tree taxa. Not only was *Metrosideros* unexpectedly uncommon in the past, but the pre-human baseline has no current analog on any northern New Zealand islands. This, and other paleoecological records from the region, demonstrate the power of the past to help inform future directions for conservation management.

(2) Examples from the tropical Andes

The Andean flank region has particularly caught the attention of researchers and policymakers due to its ecological value, and both its historical and current anthropogenic pressures (Cuesta et al. 2019). Paleoecological studies carried out in the tropical Andes have focused on using past environmental information to anticipate future scenarios of global change, including: (1) observing the synchronicity between environmental change and societal restructuring and adaptation in pre-Columbian populations (Gosling and Williams 2013); (2) pinpointing potential microrefugia locations based on the past dynamics of the Andean flag taxon *Polylepis* sp. (Valencia et al. 2016); and (3) highlighting shifted historical baselines such as those observed in the 19th century in locations with large pre-Columbian anthropogenic pressure that suffered depopulation following European arrival (Loughlin et al. 2018).

For example, fossil pollen showed a succession of Andean forest driven by changes in land-use. This forest succession was divided into five different vegetation baselines (Loughlin et al. 2018): pre-European (pre-CE 1588 indigenous occupation), successional (CE 1588–1718 European arrival/re-colonization), mature (CE 1718–1819 diminished population), deforestation (post CE 1819, re-colonization), and modern (industrial

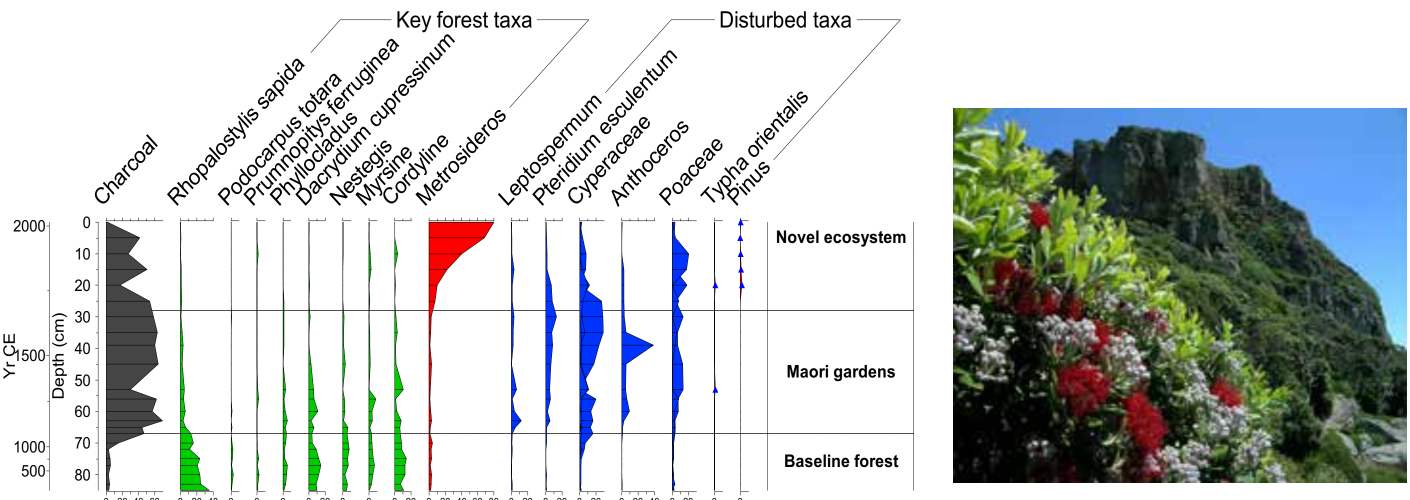

Figure 1: Example from Tawhiti Rahi Island of the Poor Knights Islands (Wilmshurst et al. 2014). Pollen data shows that the current vegetation composition is completely different from ancient ecosystems (photo credit: J.M. Wilmshurst).

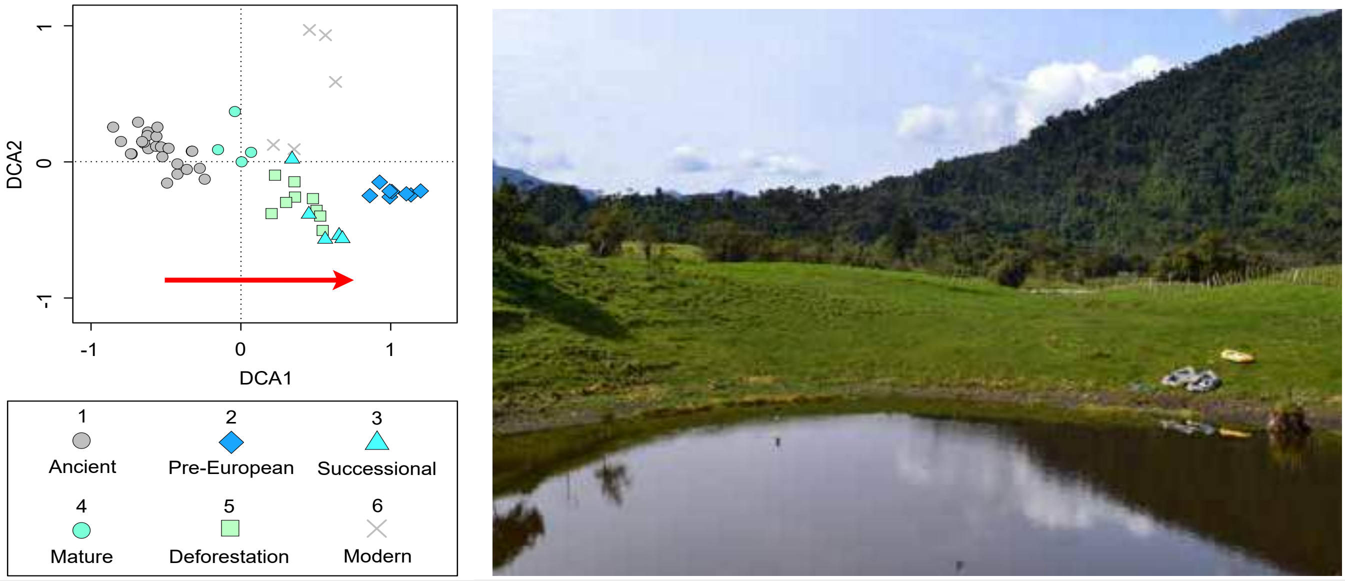

Figure 2: Detrended correspondence analysis (DCA) of pollen data from Andean montane forest grouped into time bins. Red arrow indicates an increasing signal of human impact. Replotted from Loughlin et al. (2018) (photo credit: N.J.D. Loughlin).

agriculture). These results were compared to a close site indicative of pre-human arrival vegetation (42 cal kyr BP; ancient), and showed the closest similarity with the post-abandoned mature state (Fig. 2). These new insights from sedimentary cores spanning the past three to four centuries show the potential to characterize meaningful restoration targets and reference ecosystems from paleoecological data (see Rull, this issue).

(3) The thermophilous forest of the Canary Islands

The Canarian thermophilous woodland is among the most threatened ecosystems in the Canary Islands (del Arco et al. 2010). The remnants of these woodlands are currently occupying less than 10% of their original area and are undergoing several restoration actions. Describing baselines for these woodlands have proved challenging and is limited to the available ecological information from the few woodlands remaining on the islands.

On the island of Gran Canaria, there have been several restoration programs mostly focused on laurel forest remnants, since only 1% of its original distribution remains on the island today. One program included restoring the Laguna de Valleseco as part of the LIFE Laurisilva XXI project, with a key objective devoted to education (Cárdenes 1998). When this project was implemented, the pre-human baseline for the site was thought to be laurel forest with the presence of e.g. *Ilex canariensis*, *Erica arborea*, and *Morella faya* agreeing with the potential vegetation maps that predicted its presence in the area (del Arco et al. 2006). However, a paleoecological record carried out at the same site suggested a wider distribution of the thermophilous forest in the past, including this northern area. Fossil pollen records showed the unexpected presence of thermophilous species such as *Juniperus* and the date palm (*Phoenix canariensis*) until about 2300 years ago when there was an increase in fires, and grasses and shrubs spread over the area (de Nascimento et al. 2016). Before these new insights from the pollen record, *Juniperus turbinata* was considered a rare tree on the island (del Arco et al. 2006). This mismatch between data sources highlights the utility of combining paleoecological data into restoration planning, and improving understanding around past composition and occurrence of plant communities.

In Teno, on the island of Tenerife (European Union LIFE Habitat project), the reference condition was obtained by a combination of sources, including inventories of locally remaining *Juniperus turbinata* trees and patches of Juniper woodlands remaining in the archipelago (Tenerife and La Gomera), potential vegetation maps, toponymy (e.g. place name or geographic name), and historical and recent (elderly locals) accounts, to confirm past occurrence of the woodlands (Fernández-Palacios et al. 2008). Ten years after plantation, populations of *J. turbinata* are showing positive growth trends, with eight tree and shrub species surviving, growing, and some even showing signs of reproduction (flowers and fruits) (Rota et al. 2021).

Conclusions

With these three examples, covering ecosystems varying from high-mountains to islands, and from both hemispheres, we show the importance of incorporating paleoecological knowledge and other sources of long-term data in restoration programs. There are numerous examples of paleoecological research that have highlighted *a priori* misconceptions on the definition of the natural vegetation (Bush et al. 2014), and the ability of past environmental change data to characterize landscapes that are different to those of today (Rull et al. 2017). Paleo-informed baselines may provide a useful perspective on the variability of ancient systems, the magnitude of biodiversity change, novel ecosystems, and responses to successive waves of cultural transformation.

ACKNOWLEDGEMENTS
This work was supported by the Spanish Ministry of Science and Innovation (CGL 2009-10939), the Open University through a scholarship to N.J.D.L. (NE/L501888/1), and a NERC fellowship to E.M. (NE/J018562/1).

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doi.org/10.22498/pages.30.1.6

Paleoecology-guided ecosystem management and restoration in the Western Mediterranean

César Morales-Molino and Christoph Schwörer

Drawing on several case studies from the Iberian Peninsula, we show how specifically designed paleoecological research can be a useful tool to guide ecosystem management, conservation, and restoration.

The Mediterranean region is well known for its outstanding diversity of species and ecosystems. This natural heritage is, nevertheless, threatened not only by ongoing climatic change, but also by legacies of multi-millennial land use and shifts in land-use patterns, which can significantly alter natural disturbance regimes. This raises questions for management and restoration of ecosystems that can be informed by long-term data from paleoecology. Here, we discuss three examples from the Iberian Peninsula that relate to fire management, herbivore management, and the conservation of cultural landscapes.

Changing fire regimes and their impact on *Pinus nigra* forests

Depopulation of rural areas and abandonment of traditional farming practices are currently leading to increased woodland encroachment, and subsequent accumulation of dead biomass (Keeley et al. 2012). Under particularly favorable conditions for fire spread and the presence of (usually anthropogenic) ignition sources, these landscapes offer the perfect setting for catastrophic fires. Concerned by this relevant and increasingly pressing issue, ecosystem managers often try to adapt forest management strategies to prevent these large and severe fires, or at least limit their spread.

In the Northern Iberian Plateau (central-northern Spain), we investigated the causes of the regional demise of *Pinus nigra* forests during historical times using a multi-proxy approach including pollen, conifer stomata, dung fungal spores, and charcoal particles, alongside peak detection analysis (Morales-Molino et al. 2017a). The results show that pine forests were the dominant vegetation in the region for most of the Holocene, under a mixed fire regime consisting of frequent low-severity (ground) fires and rare high-severity (crown) fires (Fig. 1). Consistent with its life-history traits (Tapias et al. 2004), *P. nigra* was able to resist ground fires but, unexpectedly, stands could also recover after single crown fires despite lacking specific adaptations (e.g. serotinous cones). However, when crown fires became very frequent with the intensification of arable and pastoral farming during the Middle Ages (1200–1000 yr cal BP), pine forests rapidly declined and even disappeared regionally (Fig. 1a).

The take-home message for forest managers who want to preserve the species-rich *Pinus nigra* forests currently thriving in the circum-Mediterranean mountains is that fuel loads need to be managed using prescribed ground fires, in order to prevent high-severity crown fires. This low-severity fire regime will, in turn, also promote seedling recruitment.

Unprecedented herbivore densities and the fate of Mediterranean mires

Another worrying aspect of ongoing land abandonment, in combination with the local extirpation of natural predators, is the dramatic increase in the densities of wild ungulates that prevents the recruitment of palatable woody species and causes potentially damaging disturbance when large herds visit wetlands (e.g. mires, springs, ponds) during the dry Mediterranean summers. Managers of protected areas need scientific knowledge about the carrying capacity of these ecosystems, i.e. the herbivore densities that the ecosystem can tolerate without risking its functionality.

In the Cabañeros National Park (central-southern Spain), current densities of wild ungulates (e.g. red deer, wild boar) are so high that mires are regularly damaged, and tree regeneration is seriously affected. We conducted paleoecological research on two peat sequences to investigate the past impact of herbivore densities (wild ungulates and livestock), inferred from dung fungal spores (Baker et al. 2016), and land use on

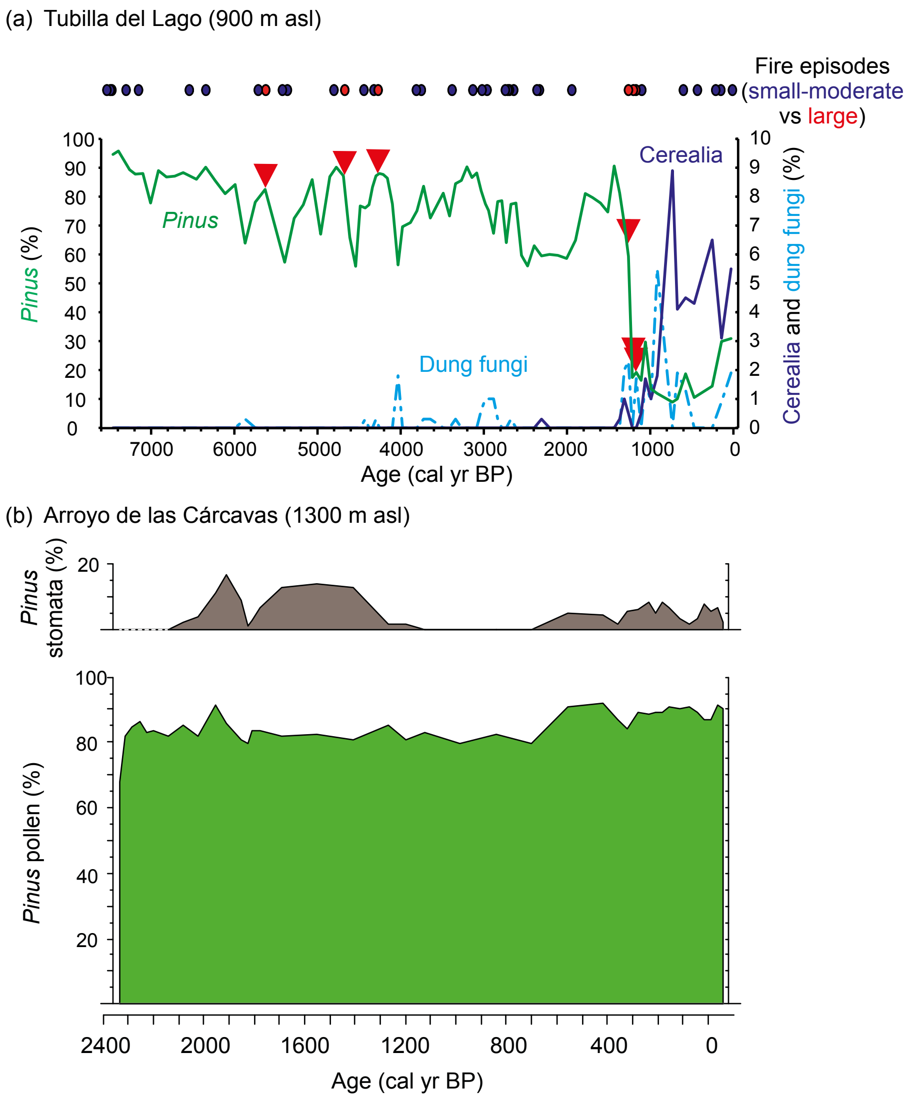

Figure 1: (A) Paleoecological record from Tubilla del Lago (central-northern Spain). Top: Fire episodes as reconstructed using peak detection analysis (Higuera et al. 2009) applied to the high-resolution macroscopic charcoal series, distinguishing between small-moderate ("surface fires") and large ("crown fires") peaks. Bottom: Abundances of *Pinus* pollen and the main local indicators of farming activities (Cerealia type, dung fungal spores). Red triangles denote the occurrence of crown fires. Modified from Morales-Molino et al. (2017a); **(B)** Pollen and stomata evidence of the dominance of *Pinus* in the Sierra de Guadarrama for the past > 2000 yr. Modified from Morales-Molino et al. (2017b).

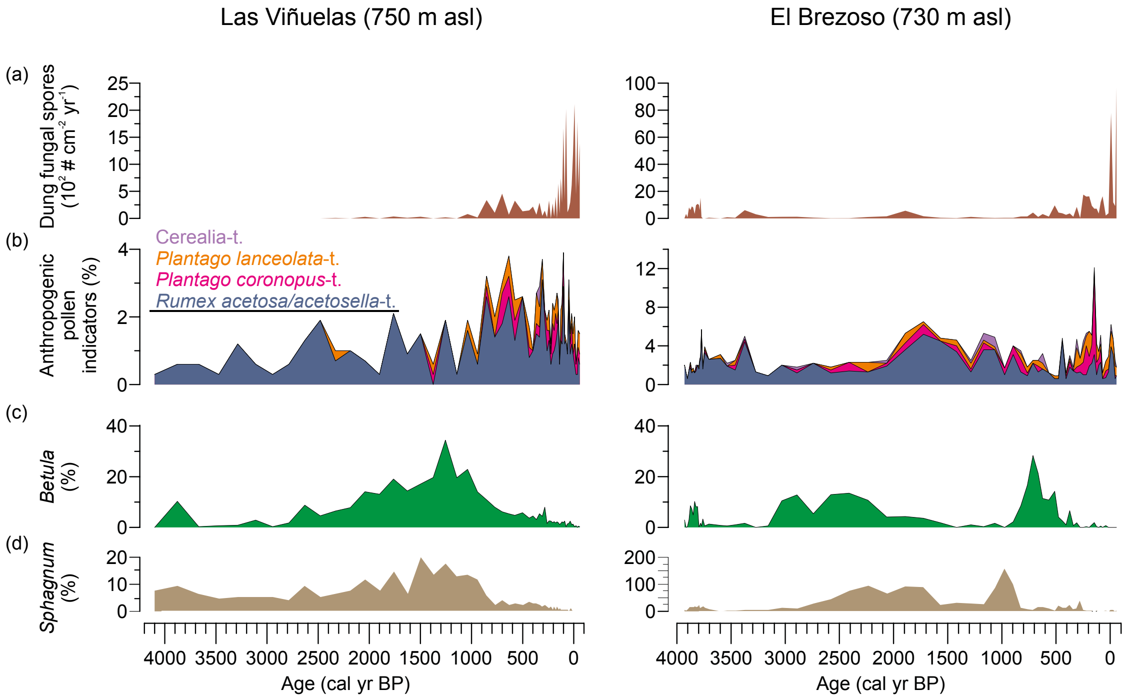

Figure 2: Paleoecological sequences from the Cabañeros National Park (central-southern Spain). Abundances of **(A)** dung fungal spores, a proxy for past herbivore density (Baker et al. 2016); **(B)** anthropogenic pollen indicators, directly or indirectly related to farming activities and disturbance; **(C)** *Betula* pollen; **(D)** *Sphagnum* spores, which are related to the extent and integrity of the mires. Modified from Morales-Molino et al. (2019).

the mires of this protected area (Morales-Molino et al. 2019). The pollen and dung fungal spore data show that locally growing *Betula* stands, as well as *Sphagnum* mats, declined and even went extinct when pastoral farming increased during the Middle Ages (1000–800 yr cal BP; Fig. 2). The influxes of dung fungal spores suggest that the extremely high current herbivore densities are unprecedented in the context of the past 4000 years. Therefore, herbivores pose a severe threat to extant mires in the region, including those where relict birch stands still survive. We strongly recommend fencing the mires to prevent further destruction by ungulates, as well as controlling the populations of these herbivores, preferably by the re-introduction of natural predators such as wolf or Iberian lynx, which went regionally extinct just a few decades ago.

What is "natural" in the Mediterranean region?

The millennial history of farming and forest use in the Mediterranean region makes it hard to assess the naturalness of certain ecosystems often considered as purely anthropogenic based on a shorter-term perspective. Precise knowledge about the "natural" composition and structure of vegetation is of paramount importance if the goal is to restore ecosystems to their "original" state, preceding the onset of heavy human impact.

The question of what the natural vegetation in an area would be remains crucial in many Mediterranean areas that were intensively disturbed by land use in the past. The "potential natural vegetation" concept, i.e. mature vegetation in the absence of human impact, has been widely used during the past few decades in this context, despite being subject to debate and controversy (e.g. Carrión and Fernández 2009; Chiarucci et al. 2010; Farris et al. 2010; Loidi and Fernández-González 2012). The long-term empirical perspective of paleoecology on vegetation dynamics, in particular in response to human impacts, allows a largely refined discussion of this topic (e.g. Carrión and Fernández 2009).

In the Valsaín forests of the Sierra de Guadarrama National Park, in the Iberian Central Range, the potential natural vegetation would consist of *Quercus pyrenaica* forests, whereas pine forests are thought to have been favored by humans (Morales-Molino et al. 2017b). We analyzed several mires using a multi-proxy approach (pollen, conifer stomata, plant macrofossils) to investigate whether *Pinus sylvestris* forests occur naturally at relatively low elevation in these mountains. The high pollen percentages along with the finds of *Pinus* stomata and macrofossils demonstrate that Scots pine has dominated forests as low as 1300 m asl for at least the past 2500 years (Fig. 1b). Paleoecological evidence therefore supports the naturalness of pine forests and refutes the need to favor *Quercus pyrenaica* in forest management.

Conclusions and outlook

The three case studies presented above illustrate how paleoecological data provide relevant information to guide the conservation and restoration of Mediterranean ecosystems. The first two examples show how paleoecological records can assist in restoring fire regimes and herbivore densities that maintain and recover vegetation. The third example shows how the long-term perspective provided by paleoecology, particularly with respect to past human impacts on vegetation dynamics, can help resolve some of the controversies raised by the "potential natural vegetation" concept (e.g. Carrión and Fernández 2009). However, we acknowledge the need for refinements and novel techniques for a broader use of these data in a global change scenario. For instance, dynamic vegetation models allow us to disentangle the past roles of climate, disturbance, and human activities in driving vegetation changes, improving predictions of future vegetation dynamics under different scenarios of climate change and land use (e.g. Henne et al. 2015; Schwörer et al. 2014). Additionally, population genetic analyses on ancient DNA preserved in plant macrofossils may provide unique information on which variant of a given tree species would be best suited to revive a population that became locally extinct in the past (Schmid et al. 2017).

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doi.org/10.22498/pages.30.1.8

The value of long-term history of small and fragmented old-growth forests for restoration ecology

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The long-term history of small and fragmented old-growth forests can provide insights into the legacies of past environmental changes and land-use history in the surrounding landscapes, which can support nature protection and restoration ecology measures.

The value of old-growth forests

Primary and old-growth forests are of great value for sustainable forest management and restoration. By virtue of their structural and compositional complexity, they are highly biodiverse when compared with managed forests in the same ecological region, as they offer a variety of microhabitats such as large pieces of coarse, woody debris, providing shelter to a range of taxa. These naturally regenerated forests of native trees are thought to have developed dynamically for a long period of time without large stand-replacing disturbances, and show no indication of human activities (Barredo et al. 2021). They offer unique opportunities to characterize the effects of natural disturbances and the structural heterogeneity emerging from natural forest dynamics. This is important knowledge to develop close-to-nature forest management practices aimed at emulating natural processes and features in second-growth forests (Schütz et al. 2016).

In Europe, primary and old-growth forests are very rare, generally small, fragmented, and less abundant (< 3% of the total forest area) than on other continents (Sabatini et al. 2018). Currently, these forests are embedded in landscape mosaics bearing variously managed patches that are sometimes strikingly different in species composition and structure. Thus, the small and fragmented ecosystems are threatened along fragment edges by land-use activities (e.g. logging) and anthropogenic disturbances (e.g. fire ignitions) that may initiate long-term changes to the structure of the remaining fragments, thereby hindering the development or the continuity of the old-growth forest stage.

Old-growth forests are typically late-successional forests that contain structures and species that are markedly different from forests of earlier stages. Their distinguishing features include high amounts of deadwood, presence of old trees approaching their natural longevity (which is often much higher than the management rotation cycle for a given tree species), and a patchwork of heterogeneously aged stands arising through small-scale gap dynamics (Barredo et al. 2021).

The current old-growthness is generally assessed using field-based methods, such as dendroecology and forest surveys, and remote sensing (Barredo et al. 2021). However, these methods cannot provide information on the longer-term history of an area. Paleoecology, instead, is sometimes the best, and only, tool for documenting the continuity of forest ecosystems and the legacies of land-use history, climate change, and disturbances (such as fire) on present-day forest composition. This information is critical for clarifying conservation and restoration objectives because mosaic landscapes are often the result of legacy effects arising from complex interactions between natural and human disturbances (Whitlock et al. 2018). In this context, stand-scale paleoecology can be particularly valuable as it allows us to address the history of small and fragmented ecosystems (Bradshaw and Zackrisson 1990; Foster et al. 1996).

Old-growth forests remnants in the Balkans

The causes of the current fragmented distribution of old-growth forests in Europe is a long-standing question in ecology. They are arguably remnants of formerly larger extents of "primeval forests", "virgin forests", "climax forests", or "Urwald" that have been shattered due to major human imprints on forest ecosystems over past millennia (Birks and Tinner 2016). However, primary and old-growth forests are particularly abundant in some regions, such as the Dinaric Alps, possibly due to early protection of forests and lower historical human pressure compared to other mountain ranges in Europe (Sabatini et al. 2018). Indeed, this mountain region is characterized by rugged terrain and land with low agricultural productivity (Kaplan et al. 2009). Nonetheless, detailed records documenting long-term vegetation dynamics, in conjunction with environmental changes, are lacking for the montane zone in this region (Finsinger et al. 2017).

Legacies of past land uses at an old-growth forest's fragment edge

Cagliero et al. (2021) recently presented stand-scale paleoecological records, an assessment of contemporary forest structure, and dendrochronological data from the edge of the Biogradska Gora old-growth forest (Dinaric Alps, Montenegro), one of the largest in Europe. It provides new insights into the long-term dynamics of these fragmented ecosystems. Like other old-growth

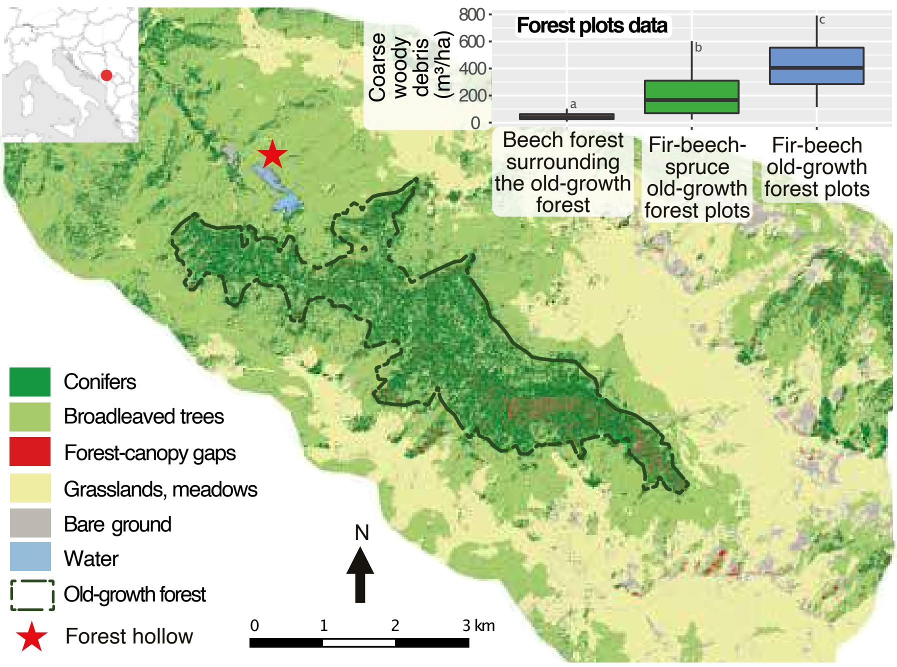

Figure 1: Distribution of land-cover types in the Biogradska Gora valley (Dinaric Alps, Montenegro). The boxplot shows the amount of coarse woody debris inside and outside of the old-growth forest (modified from Cagliero et al. 2021).

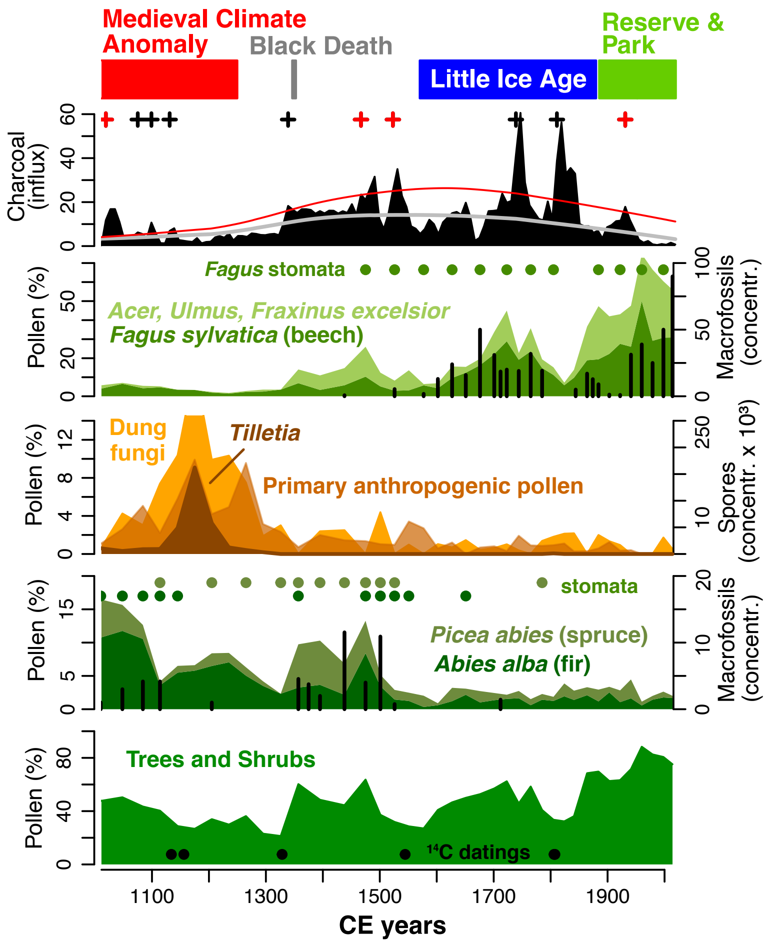

Figure 2: Local vegetation and fire-disturbance dynamics at the current edge of Biogradska Gora's old-growth forest as reconstructed with the sediments from a small forest hollow. The charcoal-influx graph includes the long-term trend of charcoal accumulation (grey line) and identified fire episodes (crosses; red crosses: higher-severity catchment fires). Pollen and spores (filled areas), stomata (full circles), and plant macrofossils (black bars) illustrate the vegetation dynamics and land-use history (primary anthropogenic pollen and *Tilletia* spores: cereal crop cultivation; cattle herding: dung-fungi spores). Full black circles (bottom) show the location of radiocarbon dates (modified from Cagliero et al. 2021).

forests in the montane zone of the Balkans, Biogradska Gora's old-growth forest is dominated by fir (*Abies alba*) and beech (*Fagus sylvatica*) with sparse spruce (*Picea abies*) (Motta et al. 2015). However, unlike many other old-growth forests, this one is surrounded by grasslands and meadows, and by almost pure beech stands. These stands are characterized by small, mostly multi-stemmed trees, the amount of coarse woody debris is negligible (Fig. 1), and charcoal kilns are present. By contrast, the fir-beech-spruce dominated old-growth forest has a mixed and multilayered structure shaped by gaps of different sizes, a large amount of coarse woody debris, and very large and old trees (> 500 years old), indicating that this part of the forest developed dynamically for a long period of time without human and natural stand-replacing disturbances.

The well-dated pollen, spore, stomata, plant-macrofossil, and charcoal records from a small forest hollow at the current edge of the old-growth forest (Fig. 1) document the reduction of fir and spruce during the Middle Ages, when the land was used for cereal crop cultivation and cattle herding, and after local, higher-severity catchment fires occurred (Fig. 2). This evidence supports the notion that historical land-use pressure reduced the extent of old-growth forests.

After intensive local land use ceased (in the mid-14th century, approximately at the time of the Black Death pandemic) and during the cooler Little Ice Age, beech-dominated stands developed in the area surrounding the old-growth (Fig. 2). The legacy of past land use is still visible as the almost pure beech stands show less old-growthness than other European beech-dominated old-growth forests. Conversely, the formal protection of the Biogradska Gora forest as a royal hunting reserve and as a national park since the late 19th century prevented intensive land use, and has strongly reduced biomass burned in recent times, which has allowed for the persistence of the beech stands in the buffer zone. This protected zone may offer a habitat for adaptation to future environmental changes, such as the expansion of the fir old-growth, as fir has more potential than spruce and beech under warmer and drier conditions (Vitasse et al. 2019).

Outlook

Old-growth forests have captured the attention of foresters and conservationists alike (Fröhlich 1930). However, there are still substantial conservation and restoration gaps, as primary and old-growth forests are only partially representative of the full range of European forest types (Sabatini et al. 2018). Paleoecology, in conjunction with structural and dendrochronological research, can unfold the history of Europe's primary and old-growth forests. Thereby, their responses to past environmental changes, as well as legacy effects of past land use and of disturbances in surrounding landscapes, can be assessed. This may be important as strategies for the preservation and restoration of old-growth forests should acknowledge past environmental changes, including land-use history, and anticipate future environmental changes.

Although primary and old-growth forests are generally included in protected areas (Sabatini et al. 2018), they may be vulnerable to climate change and associated changing disturbance regimes (wind, pathogens, or fire; Seidl et al. 2017). For instance, several of the smaller old-growth forests that bear fire-sensitive species such as *Abies alba* may be at risk if fire-frequency becomes excessive. In this context, identifying and protecting primary and old-growth areas and their buffer zones, as well as protecting and restoring secondary forests that may represent future primary and old-growth ecosystems (Barredo et al. 2021; EU's Biodiversity Strategy for 2030: ec.europa.eu/environment/strategy/biodiversity-strategy-2030_en) could be of paramount importance to promote native forests. Such actions may likely increase ecosystem resilience to future climate change and be helpful to anticipate environmental changes (Henne et al. 2015).

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doi.org/10.22498/pages.30.1.10

Understanding and enabling variability in wetlands

Max Finlayson[1] and Peter Gell[2]

Given changes due to the direct drivers of change in wetlands and the absence of suitable reference conditions, we recommend that the Ramsar Convention on Wetlands develops guidance for managers to better understand the nature and trajectory of change in wetlands, and to identify preferred ecological conditions.

The state of wetlands

The Ramsar Convention on Wetlands (see ramsar.org and Gell 2017 for background on the Convention) has reported that national governments are having difficulty in meeting their obligation to maintain the ecological character of internationally important wetlands (Ramsar sites) and other wetlands in their territory (Ramsar Convention on Wetlands 2018; Convention on Wetlands 2021). This indicates a need to better understand the drivers of change in wetlands to inform management decisions, and to identify the trajectories of ecological change.

Key obligations accepted by national governments under the Ramsar Convention are to maintain the ecological character of wetlands they designate as internationally important (known as Ramsar sites), and to make wise use of other wetlands in their territory (Finlayson et al. 2011; Pritchard 2021). These concepts are defined as follows: (1) the ecological character of a wetland is the combination of the ecosystem components, processes, and benefits/services that characterize the wetland at a given point in time; (2) wise use of wetlands is the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development (Finlayson et al. 2011, page 185). Hence, national governments commit to maintaining or restoring wetland ecosystems, their biodiversity, ecological processes, and ecosystem services.

Ecological character of wetlands

The ecological character of wetlands is a consequence of their history, and the ecological trajectories that have been set in place through natural succession and the influence of humans. The former may have occurred over millennia, with more recent human impact arising from pollutants and changes in land and water use within wetlands, and their catchments.

As the maintenance of the ecological character of each Ramsar-listed wetland is judged against an agreed baseline, it is necessary to identify and describe that baseline in sufficient detail for managers to use as a reference, including accommodating natural variability and ecological succession (Pritchard 2021). In some cases, managers have accepted that the ecological character at the time of listing as a Ramsar site was the appropriate baseline. However, many wetlands were in long-term ecological decline long before listing as Ramsar sites, including those documented by Gell et al. (2016). This points to a need to provide information about the nature of change in wetlands, over a range of time-scales, and to improve understanding about their present condition and the importance of anthropogenic drivers. This includes understanding whether paleoecological approaches could be combined with other approaches to understand benchmarks of change, as well as the rates and direction of change, both historic and anthropogenic.

Wetland wise use and long-term change

Guidance for the wise use of wetlands has been developed through the Convention to provide wetland managers with technical knowledge for making decisions for managing and restoring wetlands, including for restoring water regimes and limiting the spread of invasive species. This guidance has not hitherto included how to establish baselines for determining change in ecological character, nor how to respond to variations and change due to climate change (Finlayson 2013). The examples outlined below illustrate how investigations of past change and trajectories can be important for managers.

(1) Loch Ruthven, Scotland

Loch Ruthven (Fig. 1) was listed as a Ramsar site in 1996 for its role in maintaining biodiversity in a biogeographic region. Its Ramsar Information Sheet[1] (2006) identified it as a mesotrophic lake, and identified its role in supporting breeding pairs of the waterbird, the Slavonian Grebe. Short sediment cores spanning almost 200 years revealed changes in the lake (Brooks et al. 2012). Diatom-inferred total phosphorus revealed the lake to have been oligo-mesotrophic before the 1920s; it is now approaching eutrophic levels. Preserved chironomid (midges) head capsules (a measure frequently used in palaeoecological and palaeoclimate studies) showed that an increase in productivity drove increases in food resources for grebe chicks. This eutrophication trend, attributed to increased cattle stocking, has increased the security of a key bird species, central to the listing of the Ramsar site. Care will be needed to avoid a critical transition that may impact the grebes and other biota.

(2) Lake Urmia, Iran

Lake Urmia (Fig. 2), listed as a Ramsar site[2] in 1975, was the world's second largest hypersaline lake until 1995 when the water level and area started to decline; it is now almost desiccated (Alizadeh-Choobari et al.

Figure 1: Loch Ruthven has undergone eutrophication, attributed to increased cattle stocking (photo credit: S. Elliot).

Figure 2: Lake Urmia in Iran is undergoing change in response to drying conditions (photo credit: M. Moser).

2016). This led to the loss of amenity values (Schmidt et al. 2020), exposure of island refugia for waterbirds, and reduced productivity of *Artemia*, the main food for migratory flamingos (Schulz et al. 2020). Lake levels have fluctuated greatly with several high lake phases occurring through the Late Holocene (Haghipour et al. 2020); however, the present trend appears to be the result of a drying climate (Schulz et al. 2020; Alizadeh-Choobari et al. 2016) and the use of the catchment's water sources. While the drying of the lake was reported to the Ramsar Secretariat in 2011, such multi-faceted drivers of change challenge restoration efforts owing to the broad bounds of past ecological states revealed through paleoclimate records and the challenge of attributing the change to climate versus human forcing, and local-versus global-scale influences.

(3) Gippsland Lakes, Australia

The Gippsland Lakes (Fig. 3) in southeast Australia were listed as a Ramsar site in 1982. Its Ramsar Information Sheet[3] (1999) reveals changes in water quality attributable to the construction of a permanent opening to the sea in 1889 to allow for navigation and access for ocean fisheries, as well as through farming in the catchment. Hazardous algal blooms have impacted the amenity of the system, yet pigment and isotope analyses from sediment cores show that these were also naturally prevalent prior to opening, owing to nutrient releases under stratified conditions (Cook et al. 2016). In fact, the increased inflow of marine waters acted to suppress blooms owing to higher salinities, at least until the 1940s when nutrient releases from the hinterland increased lake productivity. Recent deepening of the opening has seen an increase of tidal water in the estuary and is resulting in ecological conditions that have hitherto not been previously recorded (Boon et al. 2016), with the death of fringing vegetation and sea-grass, increases in marine biota, and unprecedented cyanobacteria blooms. The system has experienced ongoing change, since well before its listing as a Ramsar site. Future sea-level rise, reduced effective rainfall, the diversion of river flows, and the further intensification of irrigated agriculture may drive the system into novel states that comprise new combinations of species, and are self-sustaining.

Supporting analyses of the trajectories of change in wetlands

These examples raise questions about the adequacy of recent baseline conditions at the time of Ramsar listing for assessing change in the described ecological character. The examples and lessons are highly pertinent to managers, given the expected onset of further change as a consequence of global forces and the inadequacy of many past baselines (see discussion in Kopf et al. 2015). Given that many baseline, or past reference conditions, may not be suitable for future management purposes, it is recommended that the Convention develops guidance to enable managers to better understand the nature and trajectory of change in wetlands and for determining preferred ecological conditions.

Figure 3: Ocean entrance to Gippsland Lakes has enabled increased inflow of marine water (photo credit: P. Gell).

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LINKS

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[3]rsis.ramsar.org/RISapp/files/RISrep/AU269RIS.pdf

doi.org/10.22498/pages.30.1.12

How paleoecology can support peatland restoration

Katarzyna Marcisz[1], S. Czerwiński[1,2], M. Lamentowicz[1], D. Łuców[1,3] and M. Słowiński[3]

As one of the worlds' most important carbon stocks, peatlands must be protected and restored. Paleoecology can be regarded as an important tool in peatland restoration and management; as decision making is a complex and intricate task, it should consider the long-term perspective of ecosystem development.

Peatlands' role in climate change mitigation

Peatlands cover 3% of the world's land area and store one-third of global terrestrial carbon, which makes them one of the most important carbon stocks (Rydin and Jeglum 2013). Saturated conditions in peatlands protect stored carbon. Healthy peatlands are also key players at the ecosystem level because they function like sponges and accumulate water in the landscape (Rydin and Jeglum 2013). Hence, they positively affect adjacent ecosystems, such as forests or grasslands.

Most peatlands worldwide have experienced significant human pressure in the past, mainly through peat extraction (Kołaczek et al. 2018) or various forms of drainage (Talbot et al. 2010), which led to the lowering of the water table. The drying of European peatlands has intensified over the last 300 years (Swindles et al. 2019), and the proportion of degraded peatlands in Europe is high (Tanneberger et al. 2021). Conservation is, therefore, crucial to prevent peatlands from turning from carbon sinks to carbon sources and to help store more water in the currently drying and warming world. Moreover, the maintenance of resilient peatlands will reduce ongoing biodiversity loss (Rydin and Jeglum 2013).

Assessing reference conditions using peatland paleoecology

Looking into the past by reconstructing long-term environmental changes is crucial to improve reference conditions for nature protection (Valsecchi et al. 2010), environmental and forest management (Hennebelle et al. 2018; Słowiński et al. 2019), and peatland restoration (Łuców et al. 2022). Reconstructed vegetation changes, hydrological fluctuations, and disturbance records (e.g. fires, human activity) can help determine potential vegetation composition, assess the extent of human impact, and single out factors that led to main vegetation transitions.

Human impacts have long-lasting consequences that are visible in palaeoecological records. For example, the effect of the establishment of drainage ditches on the Linje poor-fen (northern Poland) had immediate consequences on the local vegetation (Marcisz et al. 2015), and drainage ditches and remains of exploitation ponds are still visible on the site more than a century after drainage ceased (Fig. 1).

Peatland histories are complex and very dynamic, and it is sometimes difficult to identify reference conditions in the past that can be set as a target for nature restoration.

A paleoecological study of the Kazanie fen (western Poland), an alkaline fen that is now under restoration, shows a diverse history of a wetland that was affected by humans over the last millennium (Czerwiński et al. 2021). Deforestation in the surrounding catchment affected its hydrology and trophic state, leading to accelerated terrestrialization of the wetland and the formation of an alkaline fen. Overexploitation of the surrounding forest, related mostly to deforestation, led to the loss of water in the catchment, which was followed by climate warming, drying and, in the end, acidification of the site. In reality, it is the anthropogenic novel ecosystem of the alkaline fen that is the target of ecological restoration (Czerwiński et al. 2021). A similar case is the Pawski Ług bog (western Poland), which is now protected as a Nature Reserve. This peatland had been functioning as an alkaline fen until ca. 700 years ago, when it switched to an acidic bog. The change was an effect of deforestation of the surrounding forests and an introduction of a feudal economy by the Knights Hospitaller (a medieval and early modern Catholic military Order of Knights of the Hospital of Saint John of Jerusalem, also known as the Joannites) who settled in the area (Lamentowicz et al. 2020). Therefore, the bog that is currently protected is, in fact, a novel anthroecosystem that is far from its pristine state.

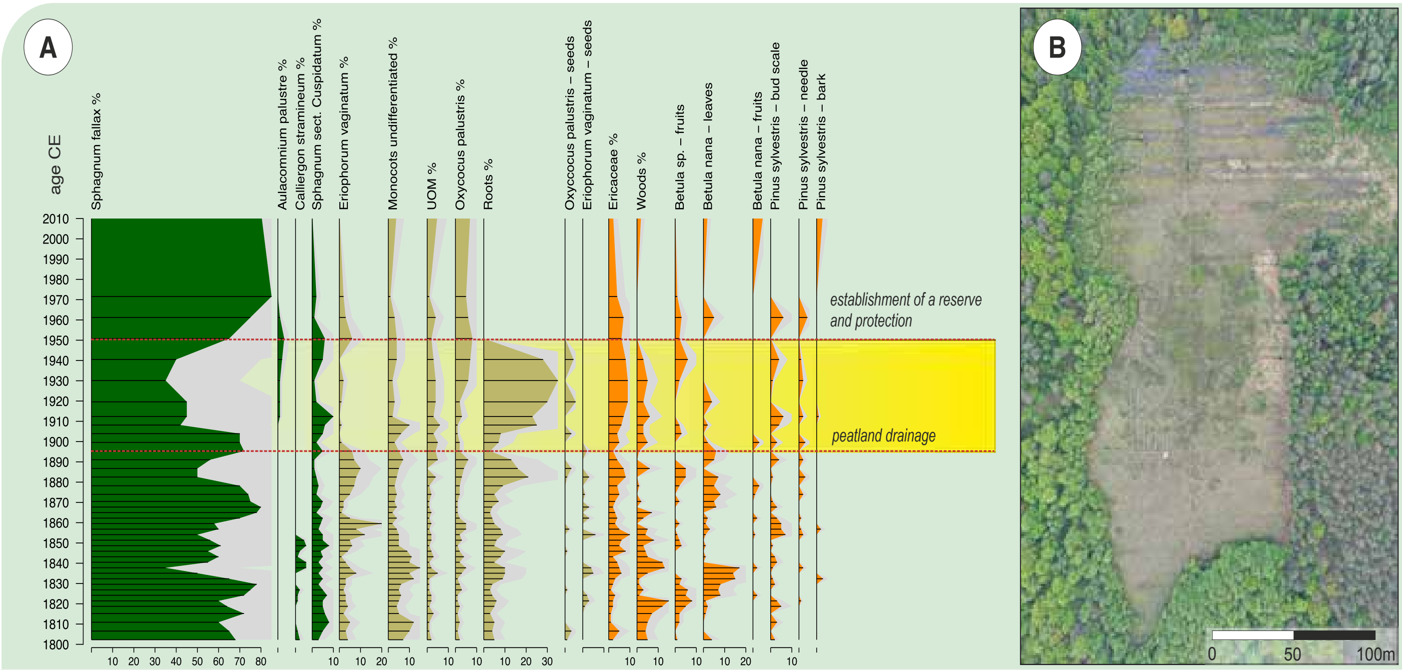

Figure 1: Linje poor-fen located in northern Poland: **(A)** paleoecological view of the effect of melioration and peat extraction at the end of the nineteenth century and **(B)** drone photo of the site taken in 2021 showing still visible areas of the drainage ditches.

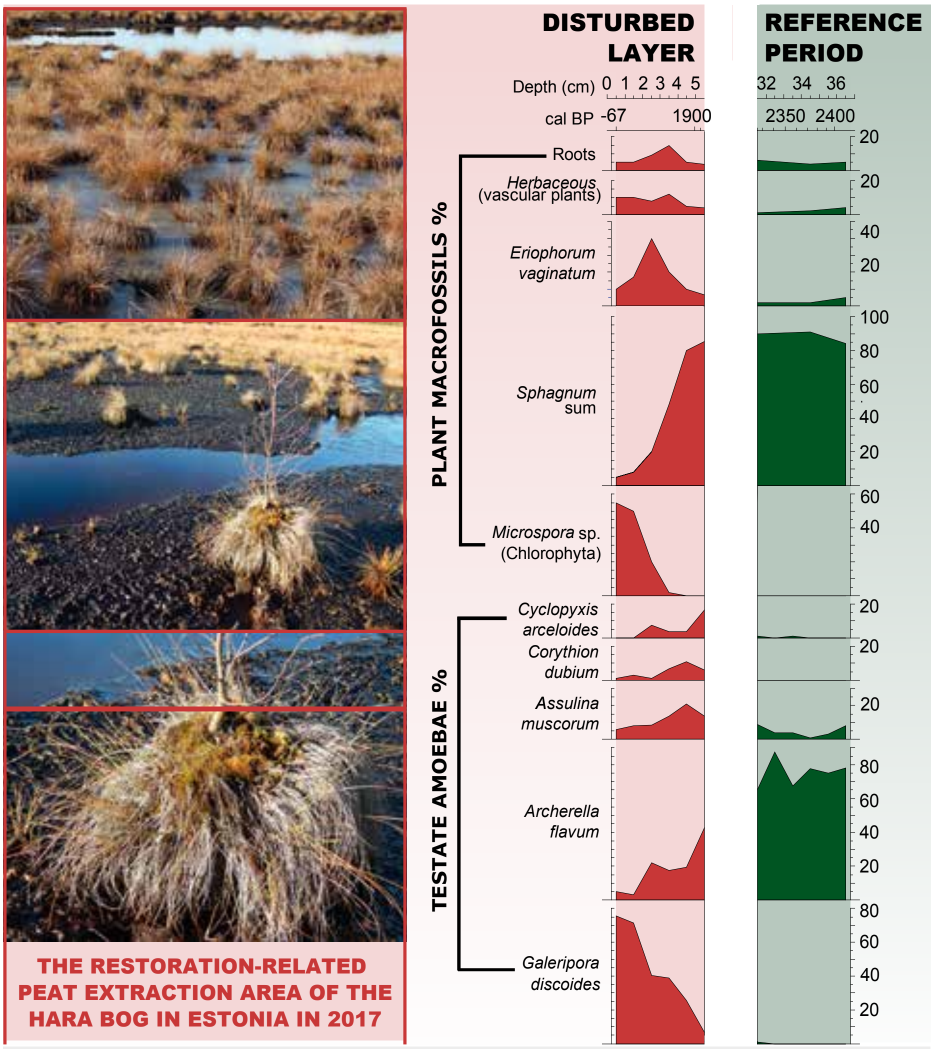

Figure 2: The restoration-related peat extraction area of the Hara bog located in northern Estonia. **(Left)** Pictures presenting the current structure of vegetation with hummocks of *Eriophorum vaginatum* and *Sphagnum* mosses, indicating fluctuations in the water table. **(Right)** Paleoecological record showing ecological contrast between restored state (current state) and pristine conditions (dated to ca. 2000 years before present) that can be regarded as a reference period for the restoration. Testate amoeba and plant macrofossil data suggest that, even though the Hara bog is far from stable and saturated conditions, it has the potential to be restored. However, the restoration of peat vegetation on bogs is a complex, difficult, and time-consuming process (figure modified from Łuców et al. 2022).

Peatland restoration efforts

In choosing proper restoration techniques, it is important to recognize the setting of the peatland, its catchment, and the factors influencing its development. Knowledge about peatland history can help implement a suitable restoration plan (Fig. 2). Yet, searching for an ecological baseline for peatland restoration may not be easy, and the efforts put into the restoration process may not result in the restoration of peatlands back to their former, pre-disturbed conditions (Łuców et al. 2022). Peatlands worldwide were influenced by various disturbance factors, and often the main one—human activity—was not present to the current extent and magnitude in the past. Therefore, it may be very hard to achieve satisfactory results in terms of biodiversity and vegetation composition.

The most common technique used for peatland restoration is rewetting drained sites using various types of dams constructed on ditches. Rewetting helps reinstate high moisture levels on the peatland and create bog-like conditions (Hancock et al. 2018), which protects carbon stored in the deeper peat and can reduce the number of peat fires (Sirin et al. 2021). However, even though novel ecosystems created through such interventions may not resemble previous peatland vegetation (Kreyling et al. 2021), e.g. be dominated by more common *Sphagnum* species or a larger proportion of vascular plants, they can still provide a carbon accumulation function that is crucial for climate change mitigation.

Furthermore, paleoecology helps us to identify the effect of restoration in the long-term context. For example, a high-resolution analysis of testate amoebae, which are very sensitive to hydrological change, can indicate even the subtle effects of the rewetting (Fig. 2; Łuców et al. 2022), enabling us to assess the effectiveness of chosen restoration techniques.

Past environmental conditions that shaped peatland vegetation and the hydrological state were very different from current ecosystem states. This, therefore, exposes a restoration paradox, the scale of which is presumably much greater than we are aware of. It opens questions of how to assess whether an ecosystem should be protected when in most cases long-term data are not considered? How to differentiate the natural succession pathways from anthropogenically induced changes in the past? And where should the restoration be directed if paleoecological data show that the protected ecosystem is the result of a past large-scale anthropogenic degradation process?

Glossary

Wetland – according to the Ramsar Convention wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters.

Peatland – a general term that characterizes an area possessing the peat (a layer usually at least 30 cm thick), while **mire** is a term for wet terrain dominated by living peat-forming plants.

Bog – ombrotrophic peatland dominated by *Sphagnum* mosses fed by rainwater, highly acidic and isolated from the minerotrophic catchment waters, might be open or wooded.

Fen – minerotrophic peatland that might be open (with e.g. sedges and brown mosses) or wooded, fed by rainwater and ground waters, alkaline and nutrient-rich.

Poor-fen – weakly minerotrophic peatland that is intermediate between fen and bog; usually dominated by *Sphagnum* mosses, but with hydrology and water chemistry like fens.

ACKNOWLEDGEMENTS

Authors were supported by the National Science Centre (Poland) (grant nos. 2020/39/D/ST10/00641, 2015/17/B/ST10/01656, 2015/17/B/ST10/03430).

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doi.org/10.22498/pages.30.1.14

The future of the past: Applications of paleoecological findings in peatland restoration in Indonesia

K. Anggi Hapsari[1], T.C. Jennerjahn[2,3] and H. Behling[1]

There are several potential practical applications of paleoecological information that can provide guidance for improving peatland restoration in Indonesia, and highlight the values, roles, and applicability of paleoecology in ecological restoration.

The importance of peatlands in Indonesia

Indonesian peatlands provide habitat for a large diversity of organisms, including endangered flora and fauna. They also store ~56 Gt carbon, equivalent to five years of current global carbon emissions, mainly in their soggy, spongy soil layers made of partially decomposed dead plant material. In the past few decades, rapid peatland degradation and drainage (Fig. 1) has not only posed a threat to the native orangutans and other species living there, who are rapidly losing their habitat, but has also facilitated peat fires, leading to haze and related health crises, and costing Indonesia billions of dollars in economic loss (World Bank 2019). Peat fires also released enormous amounts of carbon dioxide, fueling climate warming, and placing Indonesia amongst the world's top carbon emitters. It is not surprising there are growing calls for restoration.

"*Ecological restoration can be improved using paleoecology*": a statement easily found in many paleo-related publications. However, there is a dearth of examples on how paleo-information can be practically applied in restoration beyond defining pre-human-intervention baselines. Meanwhile, attempting to restore the ecosystems to their pre-human conditions is increasingly being considered to be unattainable or even inappropriate (Clewell and Aronson 2013; Baker and Eckerberg 2016; Rull, this issue). Here, we use a paleorecord from the Sungai Buluh peatland in Indonesia as our main example, where the impact of the Malayu Empire's activities and how the peatland responded to them, is documented (Fig. 2; Hapsari et al. 2018; 2021).

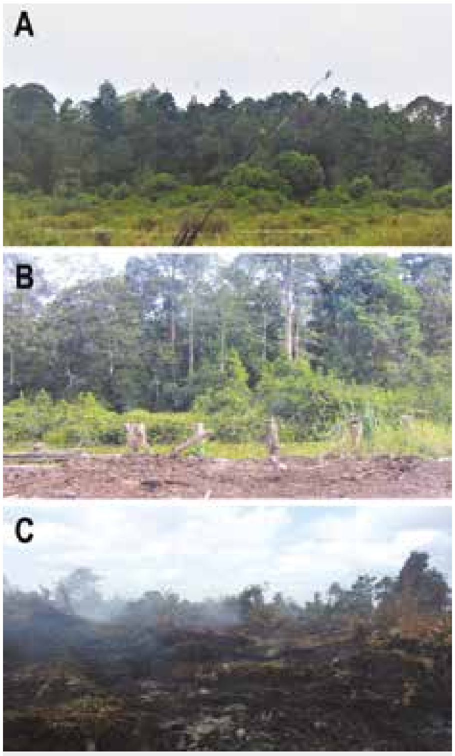

Figure 1: Images of **(A)** pristine, **(B)** degraded, and **(C)** burnt peatlands in Indonesia (photo credits: A. Hapsari and I. Fikri).

Goal adjustment

When defining what it is we are trying to restore, we can use ecological attributes of a successfully restored or undegraded ecosystem (e.g. species composition, resilience, functions) as goals (Clewell and Aronson 2013). We then need to ensure the goals are realistic and can be met within regulatory constraints and available resources.

Most, if not all, peatland restoration projects in Indonesia aim to restore both hydrology and peat swamp forests to an intact state, i.e. prior to disturbance, and refurbish their functions and values (Puspitaloka et al. 2020). These projects are typically planned for 60 years, but many are shorter (3-30 years) due to limited resources.

The paleorecord from Sungai Buluh taught us that it took 170 years for the peatland to return to its pre-disturbance condition after "light" human use (i.e. no clearing/drainage). Thus, the goals of present-day peatland restoration are quite unrealistic, as we now face much harder ecological (drained/cleared/burnt) and socioeconomic (resistance/sabotage) challenges, a much shorter timeframe, and often limited resources. It is necessary for the projects to either opt for easier goals (e.g. zero-illegal logging, blockage of all canals) or to extend the project durations, especially if the fulfillment/unfulfillment of the set goals will decide the project's fate, e.g. further funding, permit extension, or penalty.

Refine the designs

The Sungai Buluh record suggests that a peatland can fully recover if it isn't drained and still has some of the old forest remaining. Restoration projects for peatlands with these conditions can choose the low-cost prescribed natural regeneration (passive restoration) approach. The resources available can be concentrated to remove/reduce the disturbances, e.g. fire prevention, law enforcement, ecoliteracy and bioeconomy development, or alternative livelihood creation.

For the drained and deforested peatlands, assisted natural regeneration or partial/complete reconstruction is needed, which includes replanting and/or rewetting. However, although replantation in peatlands creates an alternative livelihood for the locals, it is very expensive and often fails because unsuitable taxa are used, e.g. dryland species are planted in deeply flooded conditions (canal/burnt scar). A paleorecord from Borneo shows that peatlands sometimes developed in *Pandanus*-dominated freshwater lakes (Hope et al. 2005). Replantation can then mimic natural succession by planting *Pandanus* in the deeply flooded areas (lake-like conditions) and introduce other desirable taxa once those areas are shallow enough (Giesen and Sari 2018).

For restoration to be successful, the target ecosystem needs to eventually manage to self-organize, an attribute that is mainly driven by the planted taxa's regenerating ability. The recovery of the Sungai Buluh peat swamp forest started with recruitment of taxa with high seed productivities, viabilities, germination rates, and seedling survival rates. Peatland restoration plans thus need to include those and/or other taxa with similar regenerative power and, if necessary, to introduce specific pollinators or seed dispersers (e.g. *Trigona* bees for *Shorea*).

Paleorecords also suggest that dense forest cover is the secret of peatlands' fire-resistance (Hapsari et al. 2021). To improve target peatlands' resilience to fire, forest cover needs to be grown quickly. While the current strategy chooses to plant in single-species groups, introducing a few individuals from many species and letting the "selection effect" do the work is a better option than planting a large number of poorly adapted species and having none survive.

Stream of income

In restoration, socioeconomic achievement is important, but it won't be sustainable long-term without ecological success and durability. Subsequent management of restored peatland needs to ensure that the socioeconomic activities won't jeopardize peatland resilience. The Sungai Buluh record suggests that collection of non-timber forest products and fodder, and selective/restrictive wood extraction without draining the land or burning the trees, are sustainable. A paleorecord from Borneo (Hope et al. 2005) also shows that human impact was restricted to the riversides because of access difficulties. Restoration can mimic the low level of past human disturbance by concentrating economically valuable taxa alongside natural waterways to ease people's access to their income source, thus limiting the temptation to reopen blocked canals, which cause major challenges in peatland rewetting.

Time is of the essence

Restoration, unfortunately, isn't a quick fix, but a long-term effort that requires patience and dedication (Clewell and Aronson 2013). Policy in Indonesia constrains the durations of peatland restoration projects within 60 (extendable to 100) years. Assuming that target peatlands will also require about 170 years to recover, like the Sungai Buluh, the 60-year framework is far too short. In fact, the target peatlands are often drained, thus requiring physical environment modification (rewetting), which will likely prolong the recovery time.

A major driver for restoration success is the time that has elapsed since the restoration started (Crouzeilles et al. 2017). Thus, the current policy needs to allow for some flexibility in granting permissible periods according to the projects' goals, e.g. longer duration for projects targeting a full biodiversity recovery than for projects aiming at zero-carbon emission (Hapsari et al. 2018). If the current policy remains in place, it needs to, at least, consider the substantial time lag between the completion of project tasks and the attainment of restoration targets. The 60(–100)-year permissible project length can serve as an "intervention period"; however, the restoration site should remain protected and monitored for another 60(–100) years to accommodate the development of peatlands' self-organization and self-sustainability.

A hope... and a warning!

Many people wonder whether ecological restoration is really achievable, or if it is just empty promises and a massive waste of investment (Conniff 2015; Almassi 2017). As the success of these efforts remains to be seen, the long wait may give rise to growing scepticism (Giesen and Sari 2018; Miller et al. 2021). The documented recovery of the Sungai Buluh peatland from past human disturbance certainly gives hope for tropical peatland restoration efforts as it shows that recovery is a slow process and that decades of waiting do not necessarily mean failure. However, it should also be taken as a cautionary example that it will take a whole lot longer to depave a parking lot and build back a paradise than the other way around–as in Joni Mitchell's song.*

*Big Yellow Taxi: jonimitchell.com/music/song.cfm?id=13

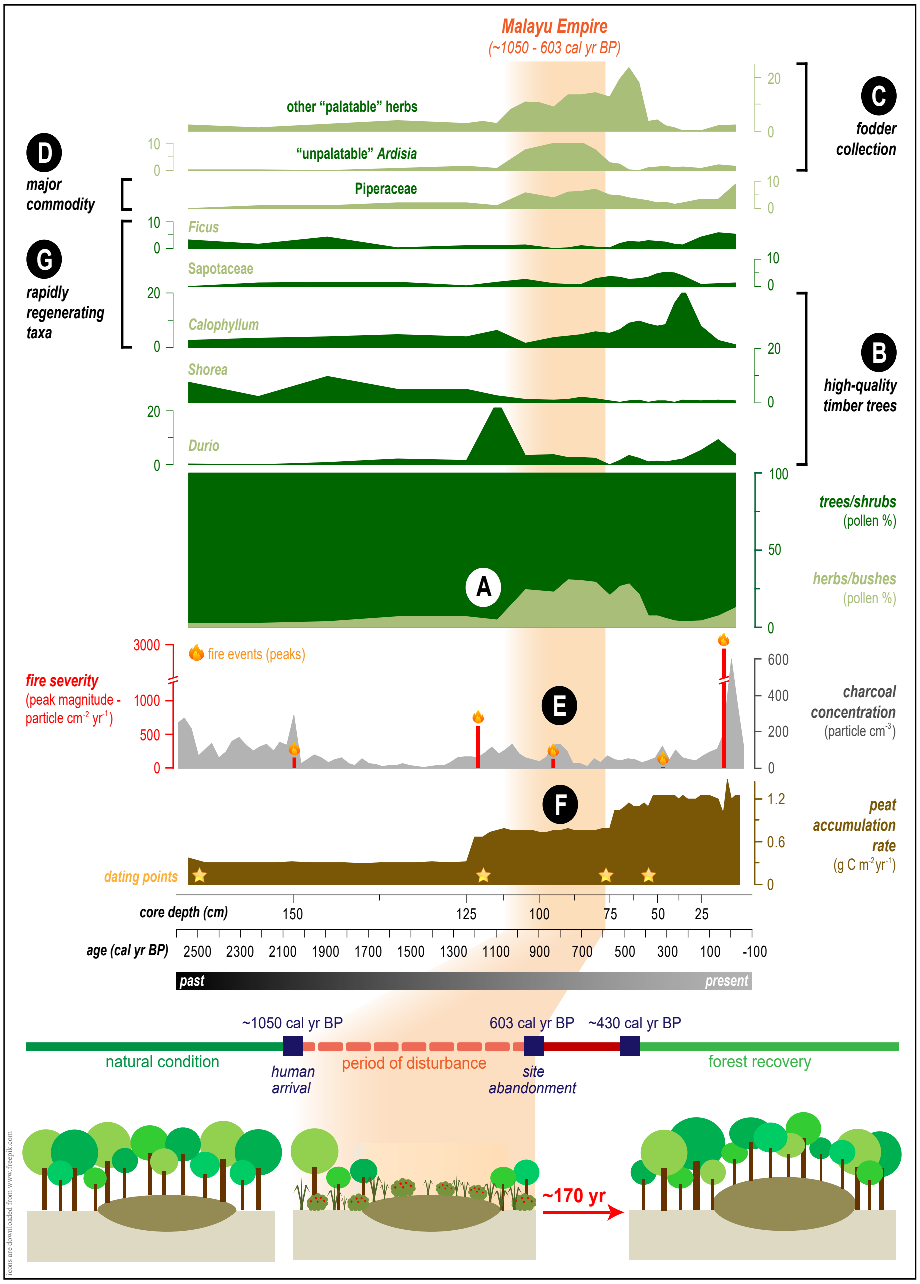

Figure 2: The Sungai Buluh peatland underwent major changes throughout the Malayu Empire occupation (orange shade; modified from Hapsari et al. 2018; 2021): **(A)** Peat swamp forest cover declined soon after the Malayu Empire arrival (~1050 cal yr BP); **(B)** A lower proportion of high-quality timber trees and historically recorded natural resource use for construction by the Malayu Empire suggests selective timber collection; **(C)** Vigorous growth of unpalatable forage that is usually driven by the lack of competition from other palatable herbs suggests fodder collection; **(D)** An increase in Piperaceae while the Malayu Empire became the largest pepper center in Sumatra implies non-timber forest product (NTPF) collection; **(E)** Relatively low charcoal concentration and peak magnitude suggests inextensive fire use; **(F)** Continuously accumulating peat substrate that needs a consistently high water-table suggests an absence of land drainage; **(G)** PSF regeneration after ME abandonment started with the increase of rapidly regenerating taxa.

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doi.org/10.22498/pages.30.1.16

The use of paleoecological data in mire and moorland conservation

Frank M. Chambers

For degraded mires and moorlands in Europe, paleoecological data from peats reveal how and when the present landscape developed. These data widen the vision of future landscapes and legitimate a greater range of targets for nature conservation agencies.

Context

The timescales and imperatives of scientists reconstructing past environments (paleoecologists), and those involved in modern ecology, have been very different (Birks and Birks 1980). Data produced by the former may be unread by, or unintelligible to, the latter, owing to the specialist journals in which they are published and their manner of presentation. Attempts to "bridge the gap" (Davies and Bunting 2010) between paleoecologists and ecologists are infrequent. Examples can be found in environments for which detailed paleoecological data are available to chronicle the past, showing how the present landscape developed (Gillson 2015). There is great potential to include these studies in restoration ecology.

Mires and moorlands

In Europe, while ecosystems responded to climate changes during the Holocene, many have also been affected by human activity over millennia. This is not always fully recognized by those responsible for their conservation. For example, in British mire and moorland environments, the most obvious human-induced effect of loss of *Sphagnum* (bog moss) species over the last century is well-known from naturalists' records, and attributed to pollution from sulfur dioxide. Yet, the long-term effects of centuries of grazing animals, at different stocking rates, with different species, is often ignored or unappreciated.

Mires and moorlands have the advantage that their underlying peats, which are incompletely decayed accumulations of plant remains, contain a record of their vegetation development over time. Analysis of these remains—pollen, spores, plant macrofossils—and of other properties of the peat, allows for reconstruction not only of their vegetation through time, but also of past climate change (Barber et al. 1994). Careful framing of multiple hypotheses permits inference of the relative effects of human activity on these landscapes.

Many nature conservationists may be unaware of the previous natural or semi-natural states of environments, beyond the past few decades. Indeed, 1949, when the national conservation agency was first established in the UK, has been used as a definitive baseline for comparative purposes of percentage habitat loss and degradation. Fortunately, enlightened staff in some of the national agencies have recognized the potential for paleoecologists to contribute much longer-term data to inform contemporary and future conservation. Nevertheless, assimilation and use of these data by conservation practitioners is not easy, requiring a more accessible form of presentation of paleovegetation data, particularly replacements for intricate pollen diagrams.

First overtures

An early attempt to combine the use of paleoecology with contemporary research into moorland restoration commenced on Exmoor, southwest England, in the late 1990s. The contemporary work, reported later by Marrs et al. (2004), but without reference to the paleo studies, had set out experimental plots investigating the use (or not) of herbicides, summer grazing (or not), and their use in combination to control and reduce the dominance of purple moor grass (*Molinia caerulea*). This dominance was regarded as undesirable in this designated Environmentally Sensitive Area (ESA), both on aesthetic grounds—the plant produced monotonous landscapes in a much-visited national park—and because it offered unpalatable grazing for stock, principally sheep. It was assumed, based on contemporary observations and oral accounts, that the purple moor grass had recently supplanted heather (*Calluna vulgaris*)—a plant regarded as aesthetically pleasing.

Palaeoecological data confirmed the relatively recent spread and expansion of purple moor grass, but unexpectedly revealed that the landscape had alternated between grass moor (with purple moor grass probably only a minor component) and heather moorland over the past millennium (Chambers et al. 1999). These results legitimized present attempts to control the hitherto unprecedented spread and dominance of purple moor grass but offered different visions of what the landscape *could* look like. Combining the two separate lines of research (experimental plots and paleoecology) suggests that generalist-feeding ponies or cattle, rather than sheep (who are finicky feeders), might help to reduce the dominance of purple moor grass.

The hitherto unprecedented stocking levels of sheep could, in part, explain the recent decline of heather and its replacement by *Molinia*. Speculatively, the combination of previous land management and grazing practices, combined with climate changes through the Medieval Climate Anomaly and the Little Ice Age, might explain the previous alternations between grass moor and heather moorland. Thus, the vision of the future landscape, upon restoration from its current monotonous state, does not necessarily have to be the replacement of one dominant (*Molinia*) by another (*Calluna*): a more diverse mosaic of grass–heather moor could be envisaged.

Degraded mires in South Wales

In South Wales, it was acknowledged that many upland mires and moorlands are depauperate, lacking some typical mire plants, particularly some of the bog moss species. This was variously attributed to overgrazing, too-frequent burning, airborne pollution, peat erosion, and climate change, among other causes. In many localities, *Molinia* was dominant.

Figure 1: Stainless-steel peat-cutter, showing safety-sheath (left) and field use (center); its sharp edge (right) ensures a clean cut, and minimal environmental damage.

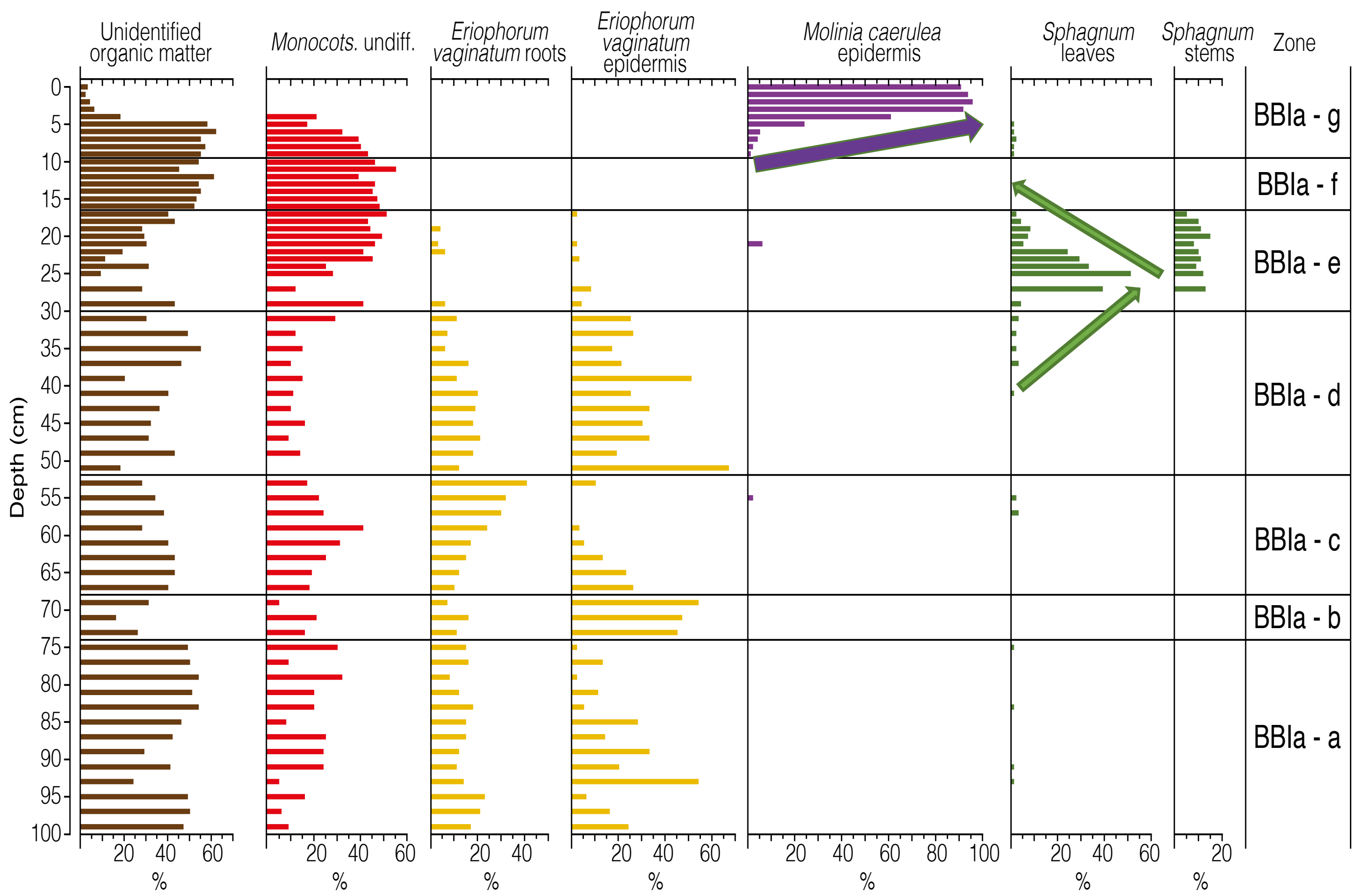

Figure 2: Paleoecological data (selected taxa) from Brecon Beacons, South Wales, showing rise and fall of *Sphagnum* (green arrows), and recent rise of purple moor grass (*Molinia*) *after* the start of the Industrial Revolution (14 cm depth).

The amount of carbonaceous pollution that fell on the uplands since the start of the Industrial Revolution had been roughly calculated (Chambers et al. 1979), and there had been the assumption that sulfurous atmospheric pollution was largely to blame for loss of *Sphagnum* species, as in the Pennines (Lee et al. 1987). However, any associated nutrient loading, which might give competitive advantage to *Molinia*, was hardly considered, and is not easy to assess. Other sources of eutrophication might be long-distance nitrogen deposition associated with agricultural practices, and the fertilizer effect of droppings from sheep at high stocking levels being fed winter feed supplement, which could result in nutrient enrichment of uplands.

On the Brecon Beacons, the current landscape is mainly treeless moorland and blanket bog. Some of the latter is eroding, with upstanding haggs (eroding blocks) of peat. The vegetation lacks diversity, with areas dominated variously by cotton sedge or purple moor grass. Palaeoecological research, commissioned by the Countryside Council for Wales (CCW; now Natural Resources, Wales), was undertaken to understand how the landscape had developed—not over the last few decades, but over the last 500 years. Radiocarbon dating showed that the peat had accumulated over several thousands of years, and so, with permission, the story was extended by taking peat monoliths economically using special field equipment (Fig. 1). The analysis of deep peat sections proved particularly useful, as it put the current vegetation state into a much longer time perspective (Chambers et al. 2013). The data showed that the current vegetation had no longevity, but rather had developed since the Industrial Revolution, with the rise of purple moor grass a recent feature after decline of centennial (but not millennial) dominance of *Sphagnum* (Fig. 2), suggesting a range of possible restoration targets.

Recent and future collaboration

In the decade since an earlier review in this magazine (Chambers and Daniel 2011), there has been limited application of palaeoecological data for mire and moorland conservation in the UK. A notable exception has been the Yorkshire Wildlife Trust, through the Yorkshire Peat Partnership, who sponsored research by McCarroll et al. (2016; 2017) on selected mires to understand better how to effect mire restoration. In Wales, too, earlier work co-published with CCW staff (Chambers et al. 2007) helped to inform conservation practice. These are exceptions rather than commonplace, and though a timely and potentially useful review of the utility of palaeoecological techniques for moorland management is available (Table 6 in Chambers et al. 2017), it has been scarcely sighted by conservation practitioners, and rarely cited. One possible reason why much mire and moorland restoration and management does not involve preceding paleoecological research is that, even with medium-term (5-yr) funding, conservation agency targets seem immediate or short-term compared with datasets covering hundreds or thousands of years. If longer-term goals were set, paleoecological research could be aligned and the long-term data generated could be better assimilated to inform the trajectory.

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doi.org/10.22498/pages.30.1.18

Paleoecology helps optimize restoration efforts by identifying unrealistic pre-anthropic targets

Valentí Rull

Paleoecological records are useful in that they inform ecological restoration efforts by not only providing the most suitable pre-anthropic baselines, but also identifying unrealistic and unfeasible restoration targets due to climatic, cultural, and economic constraints.

Paleoecology can inform ecological restoration efforts, as it may help set the expected/desired pre-anthropic ecosystem targets and baselines (Willard and Cronin 2007; Willis et al. 2010). However, past reconstructions have also identified unexpected changes in community composition, with no modern analogs, in response to environmental shifts (Williams and Jackson 2007). It has been recommended that conservation and restoration efforts focus on viable strategies and consider the possibility that novel and unexpected ecosystems will emerge in the near future as a response to ongoing global change (Jackson and Hobbs 2009; Hobbs et al. 2014). Another source of uncertainty in the definition of restoration targets is the feasibility of rebuilding pre-anthropic conditions, especially in cases where ecosystems have already crossed a tipping point leading to irreversible regime changes. Paleoecology is also able to identify unrealistic restoration targets, which may help optimize conservation efforts by helping to shape more realistic targets for restoration. This paper shows some of these situations using case studies selected according to the experience of the author, but similar situations exist elsewhere. The main past and present features of the selected areas are described (also see Fig. 1). The main paleoecological trends in each area are shown in Figure 2.

1. Gran Sabana (Venezuela)

Type locality: Several lakes and bogs from the southwestern sector of the Gran Sabana region (Rull et al. 2013).

Pre-anthropic vegetation: Dense and diverse rainforests (*Catostemma* and *Dimorphandra*) and shrublands (*Bonyunia*), possibly with scattered savanna patches.

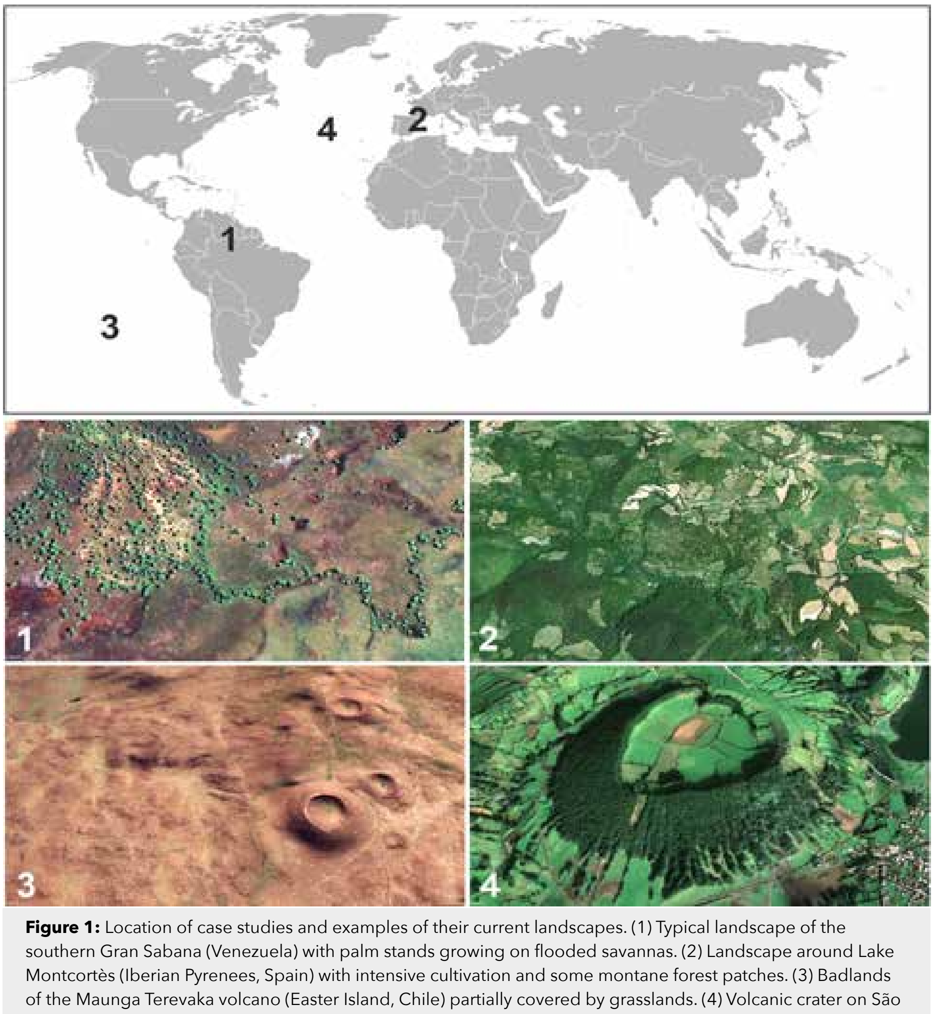

Figure 1: Location of case studies and examples of their current landscapes. (1) Typical landscape of the southern Gran Sabana (Venezuela) with palm stands growing on flooded savannas. (2) Landscape around Lake Montcortès (Iberian Pyrenees, Spain) with intensive cultivation and some montane forest patches. (3) Badlands of the Maunga Terevaka volcano (Easter Island, Chile) partially covered by grasslands. (4) Volcanic crater on São Miguel Island (Azores, Portugal) with extensive croplands and planted forests of exotic species. Images from Google Earth.

Present-day vegetation: Treeless savannas with gallery forests along rivers and palm stands of *Mauritia flexuosa* (morichales) on flooded terrains.

Current anthropic pressures: Extensive burning, surface mining, and international tourism.

Main paleoecological trends: Pre-anthropic woodlands occurred during the Younger Dryas (YD) and the Early Holocene (EH), when the climate was significantly colder and drier than that of today (13 to 10 cal kyr BP). Further burning, possibly by nomadic hunter gatherers, transformed the region into extensive treeless savannas with gallery forests along rivers. This persisted until ~2 cal kyr BP, when the indigenous Pemon people settled the region and favored the establishment of *Mauritia* palm stands using selective burning.

Main restoration challenges: Climatic and cultural. Past YD and EH climates suitable for the occurrence of pre-anthropic vegetation are impossible to reproduce in the present conditions. In addition, rebuilding pre-anthropic landscapes would imply the removal of savannas and *Mauritia* palm stands, as well as the eradication of fire practices, which constitute key resources and traditions for the Pemon people.

2. Pyrenees (Spain)

Type locality: Lake Montcortès (Rull et al. 2021).

Pre-anthropic vegetation: Lower montane forests (*Pinus* and *Quercus*) and gallery forests (*Alnus* and *Corylus*) surrounding rivers and lakes.

Present-day vegetation: Croplands, pastures, badlands, and remains of low-montane forest.

Current anthropic pressures: Intensive and extensive agriculture, forestry, and regional tourism.

Main paleoecological trends: Pre-anthropic montane and gallery forests were affected by anthropogenic fires at ~300 BCE (Iron Age) but were resilient until a second deforestation event occurred at ~300 CE (Roman Period), when croplands significantly expanded. Fires stopped at the beginning of the Middle Ages (~500 CE), but deforestation events (selective felling) continued until the Modern Age (~1800 CE). During the last century, massive depopulation of montane areas due to population emigration to industrialized cities led to the expansion of montane forests (Trapote et al. 2018).

Main restoration challenges: Cultural and economic. The full large-scale recovery of pre-anthropic forests would require the abandonment of private agricultural and forestry practices at regional scales. This would necessitate a radical change in the local culture and/or in the land property regime, a situation that would be highly unpopular and likely unviable under the present socioeconomic conditions.

3. Easter Island (Chile)

Type locality: Two lakes (Kao and Raraku) and a bog (Aroi) (Rull 2020).

Pre-anthropic vegetation: Dense forests dominated by an extinct palm that covered ~80% of the island.

Present-day vegetation: Grasslands, badlands, and scattered plantations of exotic trees (*Eucalyptus*).

Current anthropic pressures: Substantial international tourism.

Main paleoecological trends: The original palm woodlands, as old as ~40 cal kyr BP, began to be removed by Polynesian colonizers around 1200 CE using fire. This deforestation was a spatiotemporally heterogeneous process across the island ending by 1600 CE, when the entire island was transformed into grasslands and badlands. During forest clearing, the islanders (Rapanui) developed gardening cultivation techniques that facilitated their subsistence until European contact (1722 CE), which signified the beginning of the demise of the ancient Rapanui culture. Landscape degradation was greatest in the 19th century, when the island was transformed into a sheep ranch.

Main restoration challenges: Cultural and evolutionary. The small island (>150 km^2) has approximately 20,000 exposed sites and manifestations of the ancient Rapanui culture, still preserved in their original places, which were built up on a mostly deforested island. Rebuilding the original palm woodlands is not realistic under these conditions. In addition, the palm species that grew on the island are already extinct; therefore, their identity and ecological requirements are unknown.

4. Azores (Portugal)

Type locality: Lake Azul, São Miguel Island (Rull et al. 2017).

Pre-anthropic vegetation: Dense *laurisilvas* dominated by *Morella faya* and *Juniperus brevifolia*.

Present-day vegetation: Croplands, pastures, and extensive forest of exotic species, mainly *Cryptomeria japonica* (Japan) and *Pinus pinaster* (Mediterranean).

Present anthropic pressures: Intensive and extensive agriculture, forestry, and incipient tourism.

Main paleoecological trends: Pre-anthropic *laurisilvas* were abruptly removed using fire by the first European colonizers around 1400 CE, and the landscape was transformed into a mosaic of shrublands and grasslands. This persisted until ~1800 CE, when extensive reforestation with exotic tree species began to shape present-day landscapes.

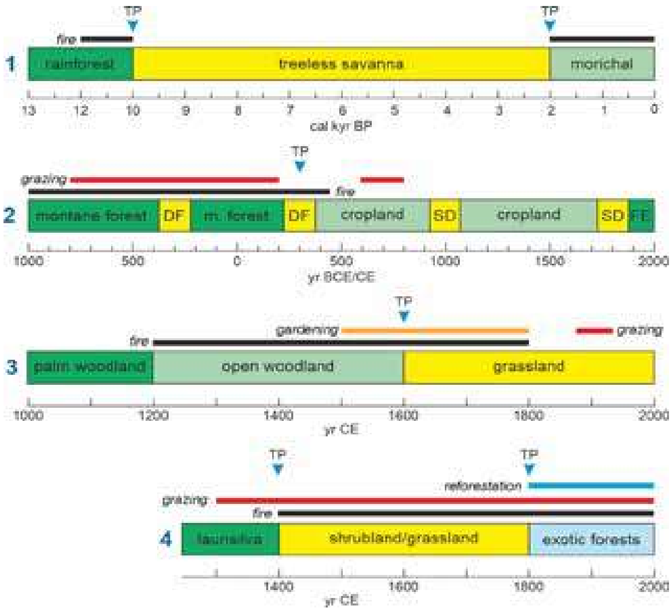

Figure 2: Vegetation changes in the areas considered in this work at three different temporal scales: The Holocene (1: Gran Sabana), the last 3000 years (2: Iberian Pyrenees), and the last millennium (3: Easter Island; 4: Azores Islands). Summarized from Rull (2020) and Rull et al. (2013, 2017, 2021). DF: deforestation using fire; SD: selective deforestation (mechanical); TP: tipping points; FE: forest expansion.

Main restoration challenges: Cultural and economic. As in the case of the Iberian Pyrenees, the eventual large-scale restoration of the original forests would require socioeconomic changes that would be difficult, or impossible, to implement under present conditions.

Restoration alternatives

The restoration impediments highlighted in the case studies above relate to large-scale or island-wide rebuilding of pre-anthropic ecosystems and landscapes, but other smaller-scale options are possible using the available paleoecological information. The possibility of restoring stands or patches representative of past plant communities outside (*quasi in situ*) or inside (*inter situ*) their natural distribution areas, either past or present, has been proposed (Burney and Burney 2007; Volis and Belcher 2010). Restoring past communities in protected areas such as national or regional parks, may also be feasible if current environmental conditions permit. Where landscapes are used for food production and other cultural purposes, a combination of these approaches would be the restoration of a series of communities that reproduce the different natural vegetation and landscape stages represented in paleoecological records to provide a historical account of the shaping of present-day landscapes.

Because paleo-inferred restoration targets can include communities that existed under warmer and/or drier climates or under different disturbance regimes, they may contribute to mitigate ecological global-change impacts. Specifically, these landscape mosaics may help to maintain biodiversity and, thus, important ecosystem properties and services. Ultimately, when large-scale restoration to pre-anthropic conditions is impossible, the paleodata can be used in framing realistic restoration targets at small to medium scales in multi-functional landscape mosaics. In cases such as Gran Sabana and Easter Island, where indigenous cultures are still present, the contribution of their traditional knowledge would be very useful for providing a holistic socioecological perspective that contributes to the conservation of cultural landscapes (Uprety et al. 2012; Wehi and Lord 2017).

ACKNOWLEDGEMENTS

The author is grateful to the editors of this *Past Global Changes Magazine* issue for the invitation to contribute and for their suggestions on the original manuscript. Basic research leading to the evidence discussed in this paper has been developed over the past 40 years and has been funded by a multitude of institutions and research programs from a diversity of countries; see the original data papers in the reference list for more detailed information.

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doi.org/10.22498/pages.30.1.20

Towards integrating paleoecological and traditional knowledge to preserve the Ethiopian Ericaceous belt

Graciela Gil-Romera[1,2], M. Fekadu[1,3], L. Bittner[4,5], M. Zech[4], H.F. Lamb[6,7], L. Opgenoorth[1], S. Demissew[3], Z. Woldu[3] and G. Miehe[8]

African mountain biomes are social-ecological systems that provide critical ecosystem services but are at risk due to increasing human pressure and climate change. Their conservation require current-day ecological analyses, but also a long-term perspective, integrating local knowledge and paleoecology.

Fire in the Afromontane biome

The Afromontane biome is a globally important biodiversity hotspot (Burgess et al. 2007), supporting the livelihoods of more than 200 million people by providing essential natural resources and ecosystem services (e.g. protection from soil erosion and floods, and water, food and timber provision) (Solomon et al. 2019). The Afromontane biome covers widely scattered mountains extending from Saudi Arabia along the Eastern Arc to Mozambique and South Africa (Fig. 1a). The biome occurs between ca. 2000 to 4000 m asl including several vegetation belts: relatively dry woodland transitioning to wetter woodland from ca. 2000 to 3000 m asl, an Ericaceous belt (EB) above 3200 m asl, and an Afroalpine biome of open shrubland and patchy grassland above 4000 m asl (Bussman 2006). African mountains have been occupied by humans for thousands of years and should be considered socio-ecological systems, wherein human agency is a key element of ecosystem dynamics. Recent studies highlight the importance of local community expertise in successful efforts to protect Afromontane vegetation (Fischer et al. 2021).

The Ericaceous belt is one of the most fragile Afromontane communities, dominated by *Erica arborea* and *E. trimera* stands (Bussmann 2006). It is especially and critically endangered by rising temperatures and unpredictable rains, rapid population growth, and agricultural expansion (Cincotta et al. 2000). *Erica* heathland is highly flammable with relatively low fire-return intervals (5–6 years), but when stands remain unburnt long enough to develop into forest (> 30 years), flammability decreases (Johansson et al. 2018). A fire-return interval between 6 and 30 years creates different degrees of heathland openness, from a dense community (Fig. 1e) to a more open one (Fig. 1f).

Despite recent research on the fire tolerance of the EB, the long-term burning tipping-points controlling *Erica* heathland sustainability are still largely unexplored. Conservation efforts in the EB have traditionally aimed to limit burning practices in protected areas, despite evidence that fire has been used as an agropastoral tool on the African continent for tens of thousands of years and current research suggesting that elimination of burning may result in high-severity fires (Johansson et al. 2018). The Ericaceous belt is one of the ecosystems where fire has long been used by people (Johansson and Granström 2014), and local knowledge and paleoecology therefore need to be considered in conservation planning.

Here we show how information on long-term ecosystem dynamics from the Ethiopian Ericaceous belt in the Bale Mountains National Park (BMNP; Fig. 1b) can be combined with interviews to pastoral communities of the Arsi Mountains National Park (AMNP; Fig. 1b). Both protected areas present similar vegetation and human activities, but AMNP receives less tourism, and traditional cattle and farming management is more widespread. Combining both perspectives will ideally produce an integrated scenario on past vegetation change, as well as a better understanding of local attitudes about the environment in the Ericaceous belt.

Combining past and present burning dynamics

The charcoal, pollen, and stable oxygen isotopic records from Lake Garba Guracha (3950 m asl; Fig. 1d), at the upper limit of the EB in the BMNP, provide information about Holocene fire, vegetation, and moisture availability (precipitation-to-evaporation ratio, P/E; see Bittner et al. 2020 for details on P/E ratio deduced from $\delta^{18}O$; Gil-Romera et al. 2021, 2019; Fig. 2). The data show three periods of *Erica* expansion and high fire activity (Fig. 2I, II, and III). Whether the ignition was human or natural, it is noteworthy that the periods of high fire activity occurred when moisture availability was either low or decreasing (Fig. 2c). This trend might be connected with reducing rainfall amounts, but also with increasing temperatures, as evaporation could have increased.

The first period occurred at 11-10 kyr BP (Fig. 2I), when a sparsely vegetated landscape dominated by Afroalpine taxa was progressively replaced by *Erica*-dominated heathland (Fig. 2b and d). The coeval increase in fire activity and *Erica* expansion at ca. 10.5 cal kyr BP (Fig. 2I) occurred during an overall dry interval. It seems likely that biomass accumulation occurred during the rainy season and supported high fire activity during the dry season. In the second fire-active period, between 8.2 and 5.5 kyr BP (Fig. 2II), the climate was more humid than in the first period, but fire activity and *Erica* biomass also show a degree of co-variability during a progressive dry trend (Fig. 2a–c). In both periods, burning and biomass accumulation established a lead–lag relationship,

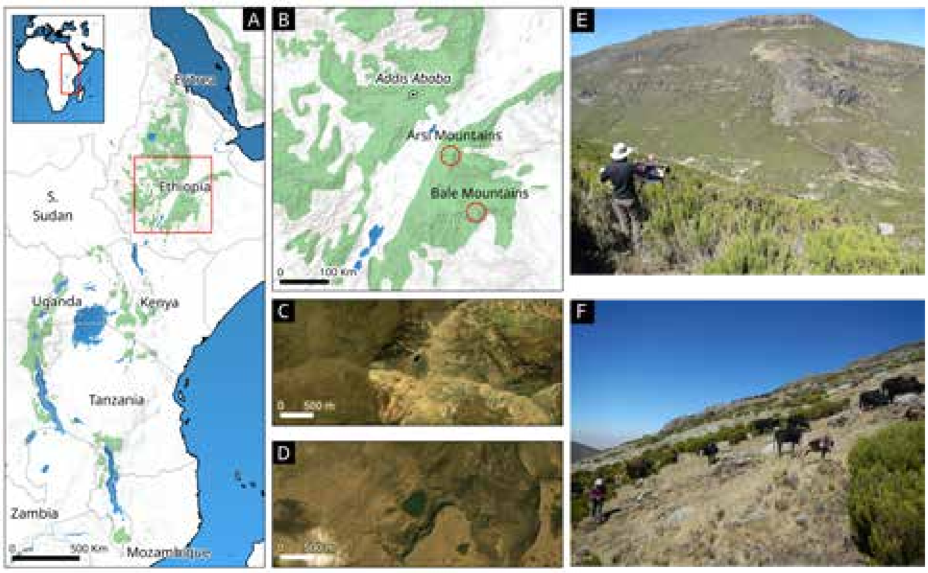

Figure 1: (A) The Eastern Afromontane archipelago; **(B)** Bale and Arsi Mountains National Parks (BMNP and AMNP respectively); **(C)** Haro Kori Lake (4000 m asl); **(D)** Garba Guracha Lake (3950 m asl); **(E)** heathland in Bale and **(F)** in Arsi areas.

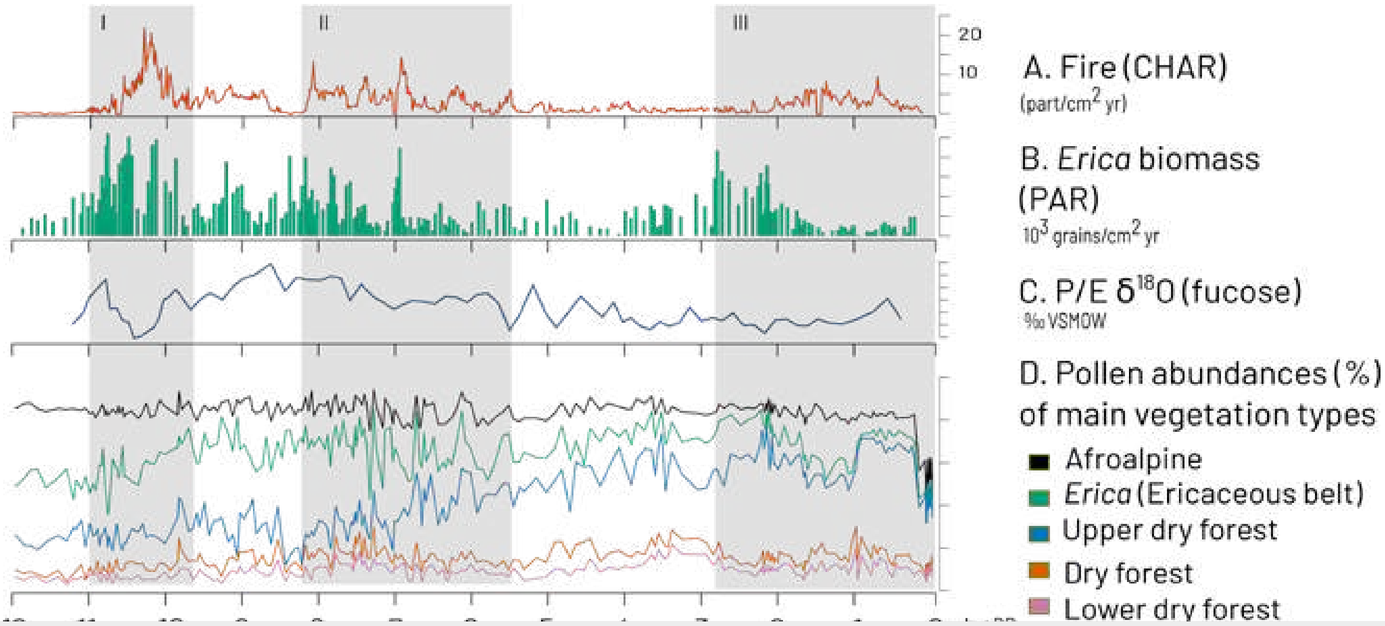

Figure 2: Paleoecological data from Lake Garba Guracha record (3950 m asl, Ethiopia). **(A)** Fire record through charcoal accumulation rate; **(B)** *Erica* abundance inferred from pollen accumulation rates; **(C)** Precipitation/evaporation ratio based on $\delta^{18}O$(fucose) isotopes; **(D)** Pollen abundances of the major vegetation zones in BMNP. Charcoal and pollen discussion can be found in Gil-Romera et al. (2019; 2021); more details on $\delta^{18}O$(fucose) are given in Bittner et al. (2020). Grey areas I, II, and III reflect the most fire-active periods.

where *Erica* was favored by fire at certain fire-return intervals, and *Erica* biomass fueled subsequent fires (see Gil-Romera et al. 2019 for numerical analyses). The third fire-active period occurred from 2.5 kyr BP to the present (Fig. 2III), under increasingly drier conditions as inferred by the P/E ratio (Fig. 2c). Fire activity was likely less intense than in previous periods, and, although *Erica* was abundant at 2.5 kyr BP (Fig. 2b and d), it decreased as the dry forest of the Afromontane biome extended upslope over the last 2500 years (Fig. 2d). The paleoecological record indicates more biomass burning during the early and mid-Holocene periods, while the EB proved to be resilient under fire frequencies between 4 and 30 years (Gil-Romera et al. 2019).

In light of the long-term environmental context, a meaningful conservation strategy would require understanding recent burning patterns in protected areas, where fire is currently banned. In February 2020, we explored the AMNP (Fig. 1b), which, unlike the BMNP (Fig. 1e), does not have dense heathland areas but rather open short *Erica* shrublands (Fig. 1f). To understand recent fire-vegetation relationships in this region, we interviewed six people from local agro-pastoral communities. Interviewees were between 30 and 40 years old and aware of landscape changes over the last two to three decades. They currently graze goats and cows and have a good knowledge of the recent burning practices in the area. Interviewees agreed that the last time the area experienced regular, large fires, aimed to produce new grass, was 10–15 years ago. Since the designation of the AMNP in 2011, burning has been banned. Two of the interviewees stated that:

"We got educated and therefore most of us do not burn any longer. However, sometimes people burn to keep hyenas away or simply as a tradition, and they send the cattle and the goats to eat the new grass and also the Erica *saplings."*

Interviewees explained that their parents' generation knew a very dense, impenetrable *Erica* landscape with remnants of Afromontane forests up to ca. 3000 m asl in AMNP. Interviewees were also aware that *Erica* plants, as well as grass cover, can return to a relatively dense shrubland within 2 to 4 years after a fire, in agreement with scientific understanding (Johansson et al. 2018). Despite the fact that burning was more frequent 20 to 30 years ago, fire was managed with return intervals of 4–5 years, which enabled the *Erica* heathland to become more dense.

On future integrative research

The evidence from paleoecology and local community knowledge suggests that past burning patterns in the Ethiopian highlands occurred under fire-conducive climates and seasonal biomass accumulations. We also inferred that intermediate fire return intervals, between 4 to 30 years, may have sustained a continuous *Erica* cover. The results suggest that a total fire ban will lead to important changes in EB structure and high-severity fires, given current increasing temperatures and population. Many questions remain about the extent to which local knowledge and recollections of past burning practices match the findings from high-resolution pollen and charcoal records in the area or other fire-information sources, such as remote sensing data. We plan to continue our paleoecological research in the Arsi Mountains by examining other lake-sediment records (e.g. Haro Kori Lake, Fig. 1c) as well as starting new calibration studies including the local knowledge and communities perspectives.

ACKNOWLEDGEMENTS

This contribution is part of the DFG project FOR 2358 "The Mountain Exile Hypothesis". The Department of Plant Biology and Biodiversity Management (Addis Ababa University), the Frankfurt Zoological Society and the Ethiopian Wolf Project Programme are acknowledged for all their support during our research. We thank the Ethiopian Wildlife Conservation Authority for providing us a research permit to work in Bale and Arsi Mountains National Park. We thank Katinka Thielsen, Terefe Endale, Abdela, Geremew Mebratu, Wege Abebe, and Awol Assefa for their support. The authors would like to dedicate this manuscript to all the Ethiopian people, currently struggling with civil unrest and armed conflict. Access to the full audio file with the interview is available upon request; please contact Graciela Gil-Romera.

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doi.org/10.22498/pages.30.1.22

The role of paleoecology in restoring and managing the Patagonian landscape

William P. Nanavati[1,2], C. Whitlock[3,4] and A. Holz[1]

Two studies from the Patagonian forest-steppe ecotone (36–55°S; Argentina and Chile) demonstrate how interdisciplinary research combining paleoecological, archaeological, and historical methods provide information on past landscape conditions that can help prioritize conservation efforts and assess the likelihood of restoration success.

The forest-steppe ecotone in Patagonia (36–55°S; Argentina and Chile) is a striking vegetation transition between the dense forests of the Andes and the vast steppe of eastern Argentina (Fig. 1). On the western side of the ecotone, mesic forest is maintained by high levels of moisture and infrequent, moderate-to-high-severity fires, whereas on the eastern side, steppe prevails in a region of high seasonal or annual moisture deficit and frequent, low-severity fires (Kitzberger 2012). Decades of paleoecological and ecological research document past shifts in the position of the ecotone as a result of changes in climate and fire activity occurring over millennial to interannual timescales (Whitlock et al. 2007; Kitzberger 2012; Iglesias and Whitlock 2014). Superimposed on these broad-scale climate–vegetation–fire dynamics are the landscape-to-local-scale influences of ~15,000 years of Native American land use and 200 years of Euro-American settlement, which have resulted in changes in site-specific vegetation, fuel loads, and fire regimes (Iglesias and Whitlock 2014; Holz et al. 2016; Nanavati et al. 2022).

The potential for landscape restoration depends on understanding the origins of the landscape condition, including the legacy of past climate and human activity (Gillson and Marchant 2014; Whitlock et al. 2018). Present landscape conditions lie along a gradient from *minimally altered* (or "nearly pristine") to *mosaic* to *intensively altered* (Fig. 2a); key to understanding ecosystem resilience within these landscapes is knowledge of antecedent climate variations, disturbance events, and land use.

In minimally altered landscapes, found in some national parks and other protected places, the influence of past climate change and indigenous land use on ecosystems cannot be easily disentangled. The assumption is that present ecosystem dynamics are operating within a range of variability shaped by climate–fire–human interactions that have not changed substantially through time. Paleoecological data, historical/ethnographic accounts, and ecological modeling are used to define an historical range of variability (HRV) for ecosystems in minimally altered landscapes, and this information establishes a baseline for restoration (Keane et al. 2009). Although ecosystems are expected to respond similarly to present-day disturbances as they have in the past, this assumption will be challenged given the novelty and uncertainty of future climate conditions (Williams 2021). Management objectives for minimally altered landscapes are, thus,

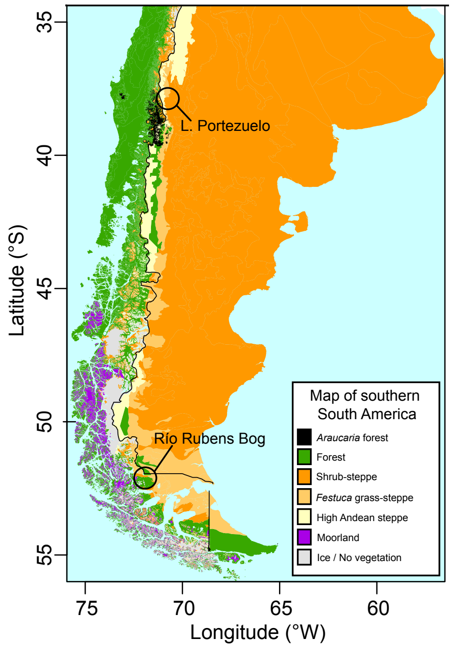

Figure 1: Map of southern South America (Chile and Argentina), showing generalized vegetation types and the ecotonal transition from wet, western forests to dry, eastern steppe. The locations of Laguna Portezuelo (Nanavati et al. 2020) and Río Rubens Bog (Huber and Markgraf 2003) are provided.

commonly to monitor and protect ecosystems from new or extreme disturbances that may signal a shift in frequency, severity, or seasonality from HRV conditions. (Fig. 2a).

At the other end of the spectrum, intensively altered landscapes have been measurably shaped by past land use through, for example, the loss of native biodiversity, changes in long-term fire regimes, and/or depletion in soil fertility. These ecosystems are often less sensitive to climatic or extreme disturbance events than those in more intact landscapes, and management objectives frequently support cultural values or commodity needs. Restoration of intensively altered landscapes to a minimally altered state requires an extensive and sustained effort and may be economically or tactically impractical considering current socioeconomic realities and future climate and development pressures. Along the Patagonian forest-steppe ecotone, among the most intensively altered landscapes are *Pinus* plantations, which have been planted for commercial use and climate change mitigation in some cases at the expense of native forest. These plantations have allowed the spread of non-native conifers far beyond their boundaries, decreasing biodiversity and increasing fire activity above the HRV (Paritsis et al. 2018; Nuñez et al. 2021).

An intermediate landscape condition is composed of a mosaic of varying degrees of minimally altered and intensively altered patches. The boundaries between these patches are often artificially defined by current land use rather than natural biophysical constraints (e.g. microclimate and soil characteristics). Ecosystems within mosaic landscapes often pose the greatest restoration challenge, since societal values assigned to individual patches may be vastly different, and minimally altered patches are easily converted to a more deteriorated state if unprotected or poorly managed (Whitlock et al. 2018).

Here, we suggest paleoecologically informed management strategies for conservation and restoration along the Patagonian forest-steppe ecotone by examining long-term ecosystem dynamics at two sites with different landscape conditions. The examples show that the restoration potential is determined by the levels of alteration prior to, and during, Euro-American settlement, as well as the likely impacts of climate change and intensified land use in the future.

Mosaic landscape: northern Patagonian *Araucaria araucana* forest

The northernmost extent of the Patagonian forest-steppe ecotone is home to the endemic and endangered *Araucaria araucana* (known as "*pehuén*" or "monkey-puzzle") tree, which presently grows along the Andes of Chile and Argentina (37–40°S) and in disjunct populations in the Cordillera de Nahuelbuta, Chile (Fig. 1). Along with its importance as a resource for food and wood, ethnographic accounts indicate that *Araucaria* plays a very significant role in Native American epistemology in northernmost Patagonia. For example, one of this region's largest groups referred to themselves as "Pehuenche", which translates to people (*-che*) of the *pehuén*. Based on written and oral histories, these people and their ancestors managed *Araucaria* forest through deliberate planting and frequent, low-severity burning to reduce competition from other species (dos Reis et al. 2014).

This hypothesis is supported by the sedimentary pollen and charcoal records from Laguna Portezuelo, which lies at the northern and eastern extent of *Araucaria*. Locally (within a radius of ~1 km), L. Portezuelo is surrounded by intensively altered pastureland, but the larger landscape (within a radius of ~10 km) consists of a mosaic of

Araucaria forest and steppe. Pollen data indicate that *Araucaria* grew near the site for the last ~6000 cal yr, but was most abundant after ~370 cal yr BP (Fig. 2b). Ethnohistorical accounts note increased Native American presence in the last four centuries in this region, which coincides with *Araucaria* expansion, charcoal evidence of increased fire activity, and pollen of native and non-native disturbance taxa (Nanavati et al. 2020). *Araurcaria* abundance declined in the 20th century with Euro-American farming and fire elimination.

These paleoecological insights suggest that efforts to protect native *Araucaria* forest at its eastern and northern limit must account not just for natural biophysical and climatological constraints, but also the likelihood that this species was maintained by Native American planting, protection, and burning practices. Projected increases in temperatures, aridity, and high-severity fires in the future (Masson-Delmotte et al. 2021) will complicate management of *Araucaria* in this region, and conservation efforts should consider planting and the promotion of frequent, low-severity fire, as was done prior to Euro-American settlement.

Intensively altered landscape: southern Patagonian Nothofagus forest

Río Rubens Bog in southernmost Patagonia can presently be described as intensively altered at the local (< 1 km radius) and landscape (within a ~10 km radius) scales. The pollen record indicates that closed *Nothofagus* forest (likely *N. pumilio*, known as "*lenga*", with some *N. antarctica*, known as "*ñire*") dominated the landscape for the last 5000 cal yr (Huber and Markgraf 2003). Charcoal data from the site suggest initially little-to-no fire, but fire activity rose to high levels between ~360 and 110 cal yr BP (Fig. 2c). Given the infrequency of lightning in southern Patagonia, these early fires were likely set by the Native American groups to facilitate hunting, communication, and travel. The onset of high fire activity also coincided with the early appearance of non-native *Rumex acetosella*-type pollen that suggests the spread of weeds three centuries before local Euro-American settlement in the late 19th century. Pollen data from Río Rubens Bog indicate little change in *Nothofagus* forest until the mid-20th century, when industrial logging became widespread and fire activity declined near the site (Huber and Markgraf 2003).

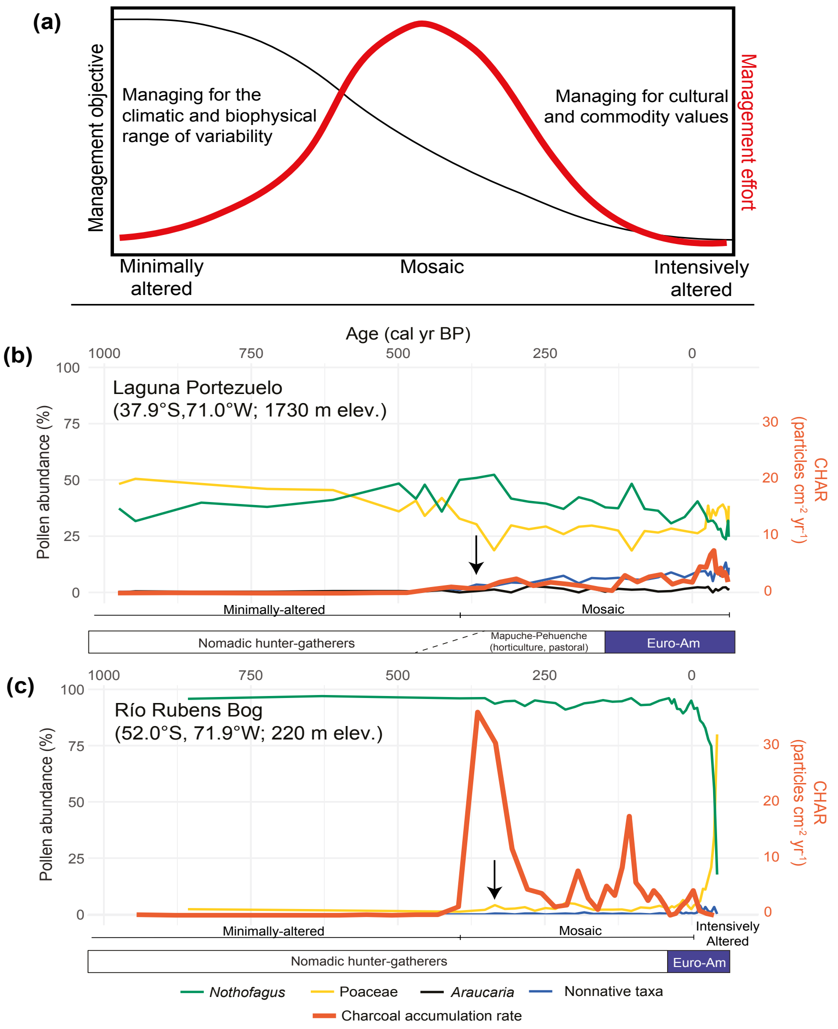

Figure 2: (A) Conceptual model for the selection of management objectives and effort based on paleoecologically informed placement of landscapes along a land use gradient (levels of alteration defined in the text; modified from Whitlock et al. 2018). **(B)** Summary plot from L. Portezuelo (Nanavati et al. 2020), showing pertinent changes in pollen, charcoal, and land-use history (diagonal, dashed line indicates gradual and dynamic transition). **(C)** Summary plot from Río Rubens Bog (Huber and Markgraf 2003), showing pertinent changes in pollen, charcoal, and land use history. Initial increases in non-native taxa are marked by arrows and landscape-scale (e.g. ~10 km radius) interpretations of alteration are provided.

In the last 100 years, Euro-American settlement and logging have greatly expanded steppe at the expense of forest cover (Fig. 2c). In intensively altered landscapes, like Río Rubens Bog, where logging and/or grazing are now widespread, conservation efforts to restore native forest are unlikely to succeed without local community support of significant land-use change. The restoration of *Nothofagus* forest in southern Patagonia will require restrictions on logging and fires, both of which will be difficult in the face of climate change and development.

Conclusions

Today's ecosystems face unprecedented rates of change as a result of anthropogenic global warming and land use (Masson-Delmotte et al. 2021). In Argentina and Chile, initiatives to restore native forests by 2035 seem increasingly unlikely to succeed given climate change projections for warmer, drier conditions, and shortages of resources and labor (Bannister et al. 2018). Paleoecological research helps contextualize the current situation within a longer ecological trajectory of change related to past climates, Native American land use, and Euro-American settlement. Whereas active restoration of intensively altered landscapes like Río Rubens may be impractical, the restoration of the *Araucaria* patches that lie within a broader forest-steppe mosaic near L. Portezuelo are more feasible with the return of indigenous practices such as controlled burns, planting, and protection. A better understanding of landscape history can, thus, inform conservation strategies and evaluate the merits of site-specific restoration efforts, as part of addressing future climate change and land use.

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doi.org/10.22498/pages.30.1.24

Millennial-scale perspective on biodiversity conservation of the forest-steppe ecotone in Europe

Thomas Giesecke[1], P. Kuneš[2] and L.S. Shumilovskikh[3]

Paleoecological studies document that grasslands with a high conservation value in the European forest-steppe ecotone are often anthropogenically derived, requiring management to avoid woodland recovery. Nevertheless, naturally open areas often persisted within this ecotone, explaining the high richness of these grasslands.

The forest-steppe ecotone

The European forest-steppe ecotone extends over 6000 km from the Carpathian to the Ural Mountains and is the natural transition from temperate broadleaf or mixed conifer forests to naturally open grasslands. Overall, this southeastern forest limit in Europe is determined by climate, while limiting parameters differ along its extent. The ecotone harbors many species-rich grasslands with high conservation value. At the same time, its Holocene history is not well documented, as indicated by the comparably small number of paleo studies in this region (Fig. 1).

The location, structure and composition of the ecotone likely changed through time as climate and land use changed over the course of the Holocene. Due to the fertile soils characterizing most of the region, it is extensively used for agriculture with few patches of natural vegetation remaining, and it is difficult to deduce the position of the ecotone based on modern observations. The transition zone may have consisted of a mosaic of forest and grasslands or uninterrupted open forest with a rich herb layer. Moreover, the mechanisms that maintained these semi-open forests or a forest grassland mosaic are not fully understood. Fires and grazing of large herbivores in combination with prehistoric land use may have shaped the structure in combination with geomorphology and local climate. Paleoecological investigations are paramount to uncover the natural position, structure, and disturbance regime to provide baselines needed for restoration efforts or management plans.

Situated at the foothills of the Ural Mountains, the Kungur region is the northern-most outpost of the East European forest-steppe zone. The high biodiversity and endemics in today's grasslands gave rise to two competing concepts describing the Holocene history of the Kungur forest-steppe. The "Pleistocene relict" concept suggests that a birch forest-steppe like those occurring in Siberia today prevailed in the region during the Pleistocene and persisted during the Holocene. The "anthropogenic" concept suggests that the Pleistocene steppe was replaced by hemiboreal forests with the onset of the Holocene, with steppe elements surviving along rivers and on exposed rocks. Deforestation led to the establishment of secondary birch and pine forests and the spread of steppe elements, as they are found today. Resolving this debate on the origin of the Kungur forest-steppe is one of the many examples of how a millennial-scale perspective can provide guidance on nature conservation and restoration.

A new pollen record documenting the vegetation composition in the Kungur region over the last 3400 years (Shumilovskikh et al. 2021) demonstrates that the landscape

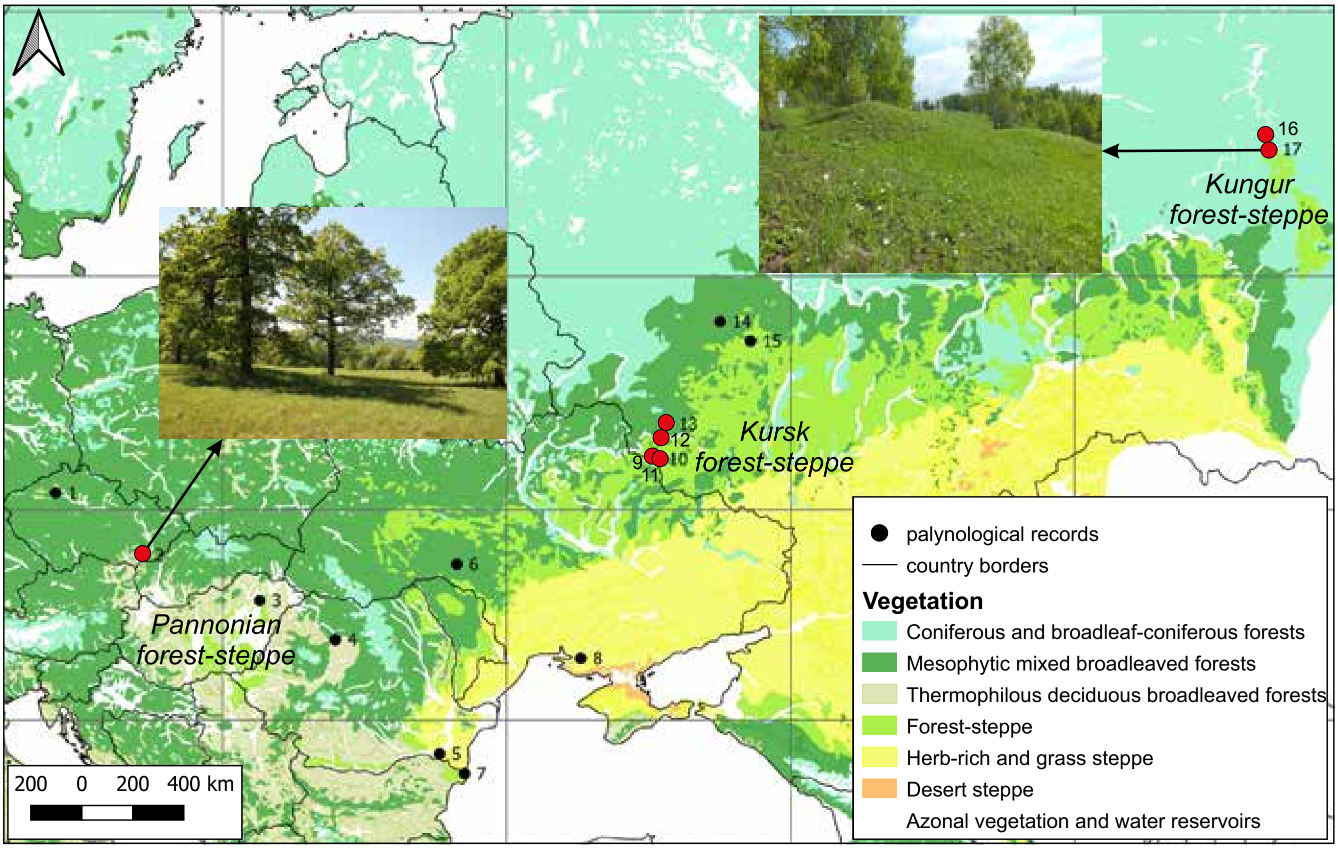

Figure 1: Map of the European forest-steppe ecotone (Bohn et al. 2003), depicting selected pollen diagrams from forest-steppe areas with those mentioned in the text highlighted in red: (1) Zahájí (Pokorný et al. 2015); (2) Lake Vracov (Kuneš et al. 2015); sites 3 to 8 are summarized in Feurdean et al. (2021); (9) Zamostye (unpublished); (10) Sudzha (Shumilovskikh et al. 2019a); (11) Klukvennoe (unpublished); (12) Peny (unpublished); (13) Razdolye (unpublished); sites 14 and 15 are summarized in Shumilovskikh et al. (2018); (16) Viatkinskoe (Shumilovskikh et al. 2019b); (17) Krugloe (Shumilovskikh et al. 2021).

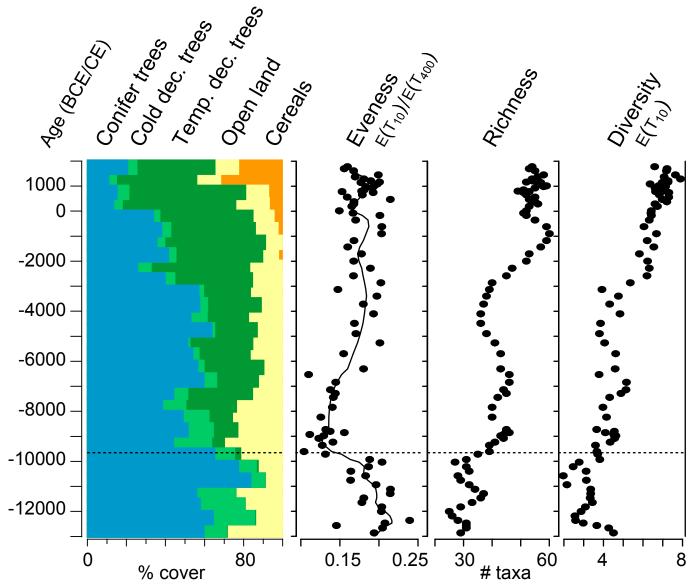

Figure 2: Pollen-based quantitative land-cover reconstruction for Lake Vracov (Kuneš et al. 2015). The ratio between forest area and open land was stable during the entire postglacial period. Reconstructed taxa are grouped into conifer trees (*Abies*, *Juniperus*, *Picea*, *Pinus*), cold deciduous trees (*Alnus*, *Betula*, *Salix*), temperate deciduous trees (*Carpinus*, *Corylus*, *Fagus*, *Quercus*, *Tilia*, *Ulmus*), open land (major herb taxa without cereals), and cereals. Pollen diversity and evenness are assessed based on the data of Svobodová (1992) following Matthias et al. (2015), and pollen-type richness is presented as a moving 4-sample taxa accumulation (Giesecke et al. 2014).

was largely covered by hemiboreal forests. The oldest samples dating to the Bronze age document the presence of humans, who created larger open areas using fire. At the end of this settlement phase, the forest recovered quickly. Nevertheless, periods with little disturbance don't have a complete forest cover. During these periods and possibly also during the Early and mid-Holocene, steppe vegetation was likely restricted to exposed gypsum formations with low water retention.

Deforestation after the Russian colonization in the 17th century led to the opening of the landscape as it is today. Thus, the generally open character of the landscape is relatively recent and of anthropogenic origin, providing new habitats for the spread of steppe species. Based on available paleoecological data, the "Pleistocene relict" hypothesis can be rejected regarding the overall openness and structure while individual steppe elements may have survived in specific habitats.

Information documenting the anthropogenic formation of open areas also comes from the middle Dniepr forest-steppe region (Kursk, Russia). The Sudzha and Klukvennoe pollen records indicate the dominance of broadleaf with oak until 200 years ago when the area was transformed into an agricultural landscape. Other sites within the region such as Zamostye, Peny and Razdolye (Fig. 1) show the presence of pine-dominated forests indicating a high heterogeneity in standscale forest composition.

High-resolution pollen diagrams for the last 1100 years from Peny show strong forest reduction in the 13th century (connected to the Kievan Rus), forest recovery during the Tatar–Mongol invasions in the 14th century, and subsequent deforestations in the 15th century (connected to the Grand Duchy of Lithuania). The last deforestation pulse occurred in the 17th century when the Tsardom of Russia erected the Belgorod defense line to protect the fertile chernozem soil region against invaders from the south. Studied records document that the forest-steppe in the Kursk region was converted into the agropastoral steppe by the end of the 17th century.

Similar vegetation histories have been described for the western edges of the European forest-steppe ecotone. Here the prevailing hypothesis of an Early Holocene closed forest that was opened through human activity (Mitchell 2005) can be rejected using paleoecology. An interdisciplinary study of Lake Vracov at the western outcrops of the Pannonian Basin documents that open vegetation persisted from the Late Glacial into the Holocene (Kuneš et al. 2015; Fig. 2). In central and western Europe, the warming with the onset of the Holocene resulted in the spread of trees or increase in tree cover. This replacement of open vegetation types is visible in pollen diagrams as a decline in pollen-type richness (Giesecke et al. 2019). The data for Lake Vracov show the opposite trend of an increase in pollen-type richness at the onset of the Holocene.

Pollen-type richness and diversity can be interpreted as floristic richness and landscape diversity (Matthias et al. 2015); both increased at the onset of the Holocene at Lake Vracov. Richness and diversity further increased around 2000 BCE with the appearance of cereals, indicating the expansion of agriculture in the region. This example shows that although there was a continuation of open vegetation types, early land use further enhanced floristic richness and landscape diversity.

In addition to this example, the Holocene persistence of open land is documented in other lowland areas in this western region (Kuneš and Abraham 2017). Paleoecological information therefore support the hypothesis that the long-term stability of these ecosystems explains the existence of species-rich grasslands, with high conservation value, such as those in the Bílé Karpaty Mountains (Hájková et al. 2011).

Conclusions

The anthropogenic origin of many European open vegetation types is documented in a multitude of palynological studies. Also, the forest-steppe ecotone was transformed by land use. While Neolithic to Iron age cultures reduced the forest cover of the ecotone somewhat, the transformation to a largely open agrarian landscape occurred only between 500 BCE in the Lower Danube region (Feurdean et al. 2021) and the 17th century in the Kungur forest-steppe (Shumilovskikh et al. 2019b, 2021). In eastern Europe, this deforestation likely shifted the ecotone to the North and West so that areas that are currently mapped as forest-steppe were forest-covered before extensive land-use started (Shumilovskikh et al. 2018).

Due to this transformation of the landscape, the cessation of agricultural activities would lead to a recovery of woodlands in most locations within the forest-steppe ecotone and a loss in the diversity of steppe associations over the medium-term. The open character of many vegetation types within the region depends on disturbance and conservation must, therefore, include disturbance factors in the form of selective felling, prescribed burning, moderate grazing, or traditional mowing.

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doi.org/10.22498/pages.30.1.26

Paleoecological records inform conservation management in New Zealand

Janet M. Wilmshurst[1,2] and Jamie R. Wood[1]

Pollen and ancient DNA from coprolites and peat reveal new and surprising insights about past pollination, herbivory, and native/alien status in New Zealand. These paleoecological findings help in understanding ecosystem structure and function before human arrival, informing current conservation, restoration, and management issues.

Oceanic islands have been transformed by forest clearance, extinctions, and invasive species following human arrival, leading to the creation of novel ecosystems (Wood et al. 2017; Nogué et al. 2021). This creates challenges for the management of current ecosystems, particularly if only relatively short-term ecological and historical observations are available to estimate what is "natural" on the landscape today (Willis and Birks 2006).

Paleoecology provides a longer-term perspective, and a more scientifically informed and defensible basis for biodiversity management decisions (Willis et al. 2007). Increasingly, paleoecological studies are providing new insights on ecological networks and interactions (e.g. pollination, seed-dispersal, and herbivory), function, and resilience (Dietl 2015), which can increase our understanding of current ecosystems and inform their management (Willis et al. 2007; Johnson et al. 2017). This is important in restoring degraded ecosystems where critical ecological functions have been disrupted.

As with many islands, initial human settlement of New Zealand ca. 1280 CE saw fundamental changes to ecosystems, largely through deforestation by fire and the rapid demise of its bird-dominated fauna (Perry et al. 2014a; Perry et al. 2014b; Wood et al. 2017). Here we showcase three examples from New Zealand where pollen and ancient DNA analyses of coprolites and peat have expanded our understanding about ecological processes and interactions and contributed to debates about contemporary conservation issues, including restoration of pollination, management of herbivores and establishing the native versus alien status of species.

Restoring ecological interactions: analysis of coprolites uncovers lost pollinators

New Zealand's endemic and threatened *Dactylanthus taylori* is a cryptic root parasite of hardwood trees and shrubs. Its current range is vastly reduced from its prehuman distribution, due to forest clearance and browsing from introduced possums (*Trichosurus vulpecula*) and rats (*Rattus rattus* and *R. norvegicus*) (Ecroyd 1996). The flowers, the only part of the plant to emerge above ground, produce copious, highly scented, and sticky nectar. The only documented pollinator is the lesser short-tailed bat (*Mystacina tuberculata*), which forages on the forest floor like a mouse (Fig. 1a). This species is also threatened and it's pre-human distributional range has become greatly reduced in area and highly fragmented (Ecroyd 1996). As *Dactylanthus* no longer co-occurs with the short-tailed bat in many places, pollination limitation provides a challenge to its conservation (Holzapfel 2005). However, Wood et al. (2012) made a surprise finding of *Dactylanthus* pollen preserved in a 900-year-old coprolite, which ancient DNA showed as belonging to kākāpō (*Strigops habroptila*), a threatened, flightless nocturnal parrot (Fig. 1a). This result suggested ground feeding and nectar drinking birds (many now extinct or rare because of mammalian predators) may also have once pollinated *Dactylanthus*. This new insight now means that besides promoting conditions for the pollinating bat *Mystacina tuberculata*, establishing *Dactylanthus* on predator-free islands

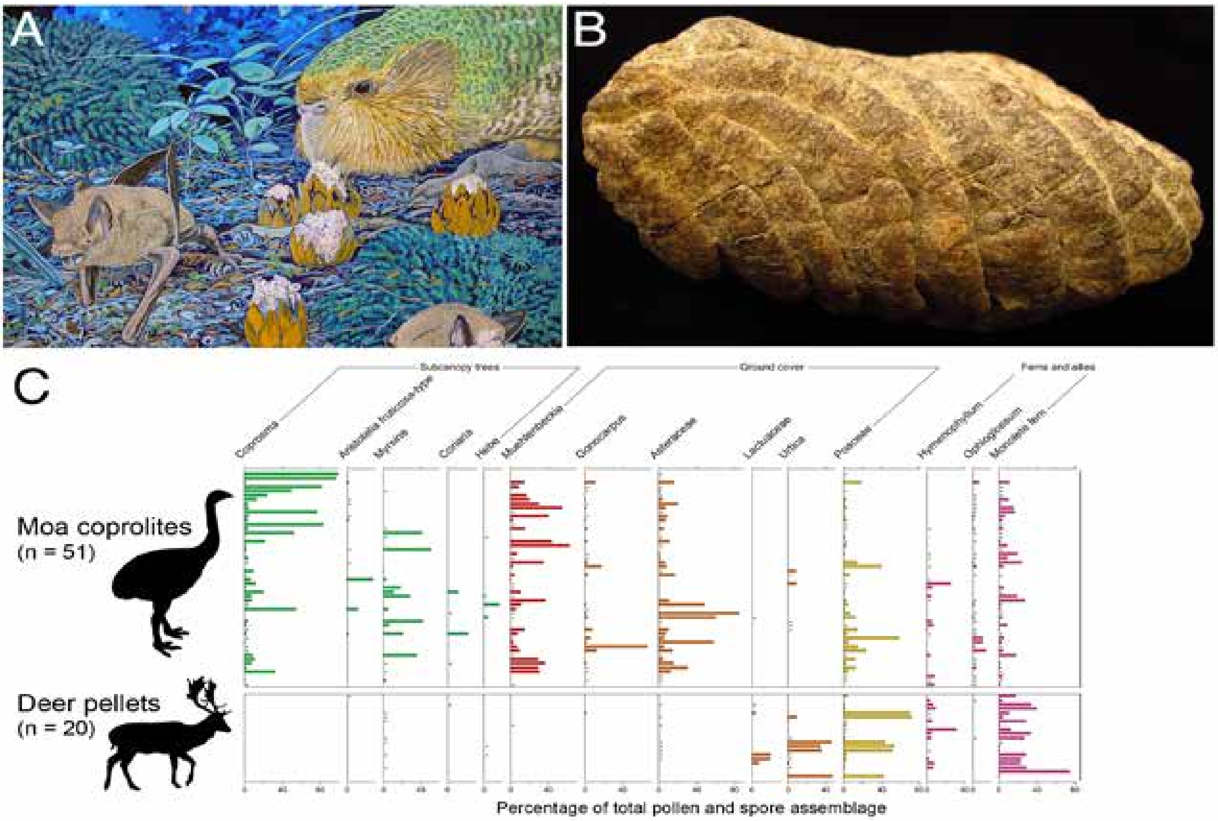

Figure 1: (A) Kākāpō (*Strigops habroptila*) and lesser short-tailed bats (*Mystacina tuberculata*) consuming nectar from *Dactylanthus taylori* flowers (from Wood et al. 2012: Artwork credit: Chris Gaskin); **(B)** Moa coprolite, Dart River Valley, New Zealand (photo credit: J.M. Wilmshurst); **(C)** Comparison of relative pollen abundance from selected forest understorey plant taxa recorded in individually sampled moa coprolites and deer pellets from Dart River Valley (modified from Wood & Wilmshurst 2019). Deer silhouette by Anthony Caravaggi (CC BY-NC-SA 3.0; creativecommons.org/licenses/by-nc-sa/3.0).

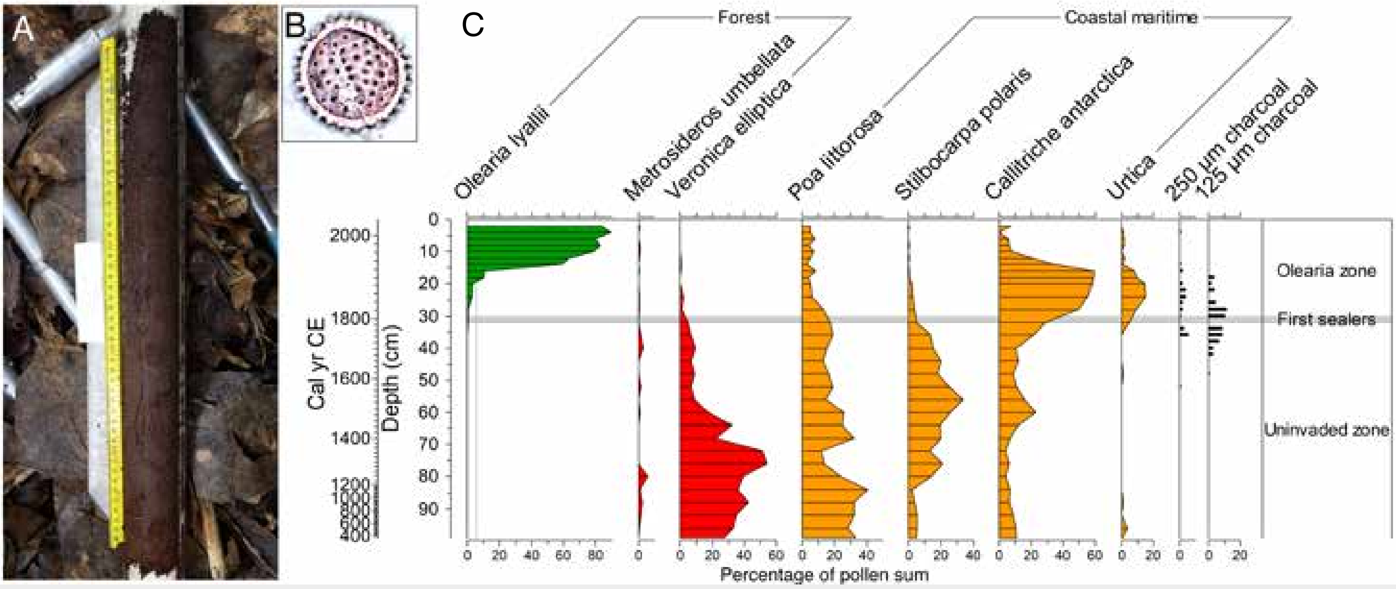

Figure 2: (A) Peat core from under *Olearia lyallii* canopy, northern Auckland Islands; **(B)** *O. lyallii* pollen; **(C)** Summary pollen and charcoal record from the northern Auckland Islands showing the recent arrival and establishment of *O. lyallii* coinciding with sealing gangs on the islands, modified from Wilmshurst et al. (2015).

with nectivorous birds is a possible solution for overcoming pollination limitation in the conservation of this rare plant.

Reconstructing past diets of extinct herbivores to inform current management of introduced herbivores

Before human arrival in New Zealand, the ratite moa were the largest of the terrestrial herbivores. Pollen, macrofossil, and ancient DNA studies of their distinctive coprolites (Fig. 1b) show that these birds browsed widely on trees, shrubs, climbers, herbs, forbs, and ferns (Wood et al. 2020). The extinction of all nine moa species by ca. 1450 CE left the large herbivore niche vacant. The introduction of ungulates from the late 1700s to early 1900s CE, including deer and goats, restored this large herbivore guild to New Zealand. However, there is ongoing debate about whether ungulate browsing is functionally equivalent to moa browsing (Wood and Wilmshurst 2017).

In 2006, coprolites (Fig. 1b) were discovered beneath a rock overhang in the remote Dart River Valley in southern New Zealand. DNA analysis and radiocarbon dating showed that they had been deposited by four different species of moa between 1,000 and 600 years ago (Wood and Wilmshurst 2019). This find was important for two reasons. First, it was within an area of relatively "natural" beech (Nothofagaceae) forest not directly modified by humans. Second, deer pellets beneath the overhang allowed a direct comparison between the diets of moa and deer. The moa coprolites contained a far greater richness of pollen types than deer pellets (Fig. 1c), suggesting that pressure from deer browsing is higher than that of moa browsing, and that deer have depleted the forest understorey of many species (Wood and Wilmshurst 2019). Many palatable plants that were common in the moa coprolites are now only found growing on the tops of enormous boulders which are inaccessible to deer. Pollen analysis of high-resolution radiocarbon dated soil cores from other relatively unmodified forests show that forest understoreys appeared to change little following moa extinction in the absence of deer (Wood and Wilmshurst 2017). These new insights from the past offer a growing scientific basis on which comparisons between extinct and introduced herbivores can be made. There is now little doubt that ungulates need to be managed to keep them at low numbers if vegetation structure and diversity similar to the past is to be maintained.

Using paleoecological records to confirm the status of an alien tree on subantarctic Islands

The longer-term perspective provided by paleoecological records (such as pollen, ancient DNA, and faunal remains in sediments or coprolites) can show if a species is native or alien and can inform decisions over whether control is needed. Wilmshurst et al. (2015) combined long-term paleoecological records from peat cores with historical photographs and documents to resolve the status and origin of a New Zealand native tree daisy (*Olearia lyallii*) growing on the subantarctic Auckland Islands, located about 450 km south of the main islands of New Zealand. The highly localized distribution of *O. lyallii* on the Auckland Islands was first noted in 1840, and its appropriate management is debated: should it be regarded as an alien invasive and controlled, or acknowledged as a native species in the Auckland Islands flora? Radiocarbon-dated pollen records from northern Auckland Islands showed that *O. lyallii* was likely absent until 1807–1810 CE (Fig. 2), which is when European sealing gangs arrived on the Auckland Islands for a brief period of seal exploitation. Sealers working on seabird islands at this time about 270 km to the north, where *O. lyallii* is naturally dominant, most likely transported the dry feathery seeds on their clothes or equipment to the Auckland Islands during this period. Pollen and charcoal records revealed that *O. lyallii* populations established and thrived in disturbed coastal areas burnt by the sealers (fig. 2). *O. lyallii* growth was enhanced by nesting seabirds and recovering seal populations using these sites, as the marine nutrients they provided replicated the situation on seabird islands in their natural range. This finding provided conservation managers with a scientifically informed basis to manage *O. lyallii* as an alien on the Auckland Islands.

Final remarks

Paleoecology can provide critical guidance for conservation management and restoration, especially in situations where other historical information or long-term ecological studies are lacking. It is therefore particularly well suited for recently settled or remote (e.g. oceanic islands) locations. However, even in ecosystems considered well-understood, it can add another dimension by revealing surprising new insights and interactions. The information can be applied in the context of functional re-wilding, herbivore management, and the control of alien species.

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doi.org/10.22498/pages.30.1.28

Using the knowledge of past ecosystem turnover to inform restoration efforts: A case study from Nigeria

Matthew A. Adeleye[1,2], S.E. Connor[1,2], S.G. Haberle[1,2] and P.A. Adeonipekun[3]

Using a paleoecological approach, we reveal that recent human activities, rather than natural variations in climate, have caused the greatest changes to Nigerian forests in the last 7000 years. Savanna has shown an even higher climate sensitivity in the past and will likely experience significant changes based on projections of future climate change.

Background

Ecosystem management and conservation challenges are acute in developing nations—including many African countries—as a result of widespread poverty, population growth, and heavy reliance of people on ecosystems for a living (Watson et al. 1997). Nigeria (Fig. 1), which is one of Africa's biodiversity hotspots (Küper et al. 2004), not only has the largest population of any African country (over 200 million), but also the highest number of people living in extreme poverty globally (fao.org; worldpoverty.io). While pervasive human impacts (e.g. agriculture, deforestation, pollution) are the major causes of ecosystem degradation in Nigeria (fao.org), the ecosystems in the region have also been impacted by recent climate changes (Ikumbur and Iornumbe 2019). Understanding the magnitude of ecosystem response (i.e. species turnover) to past climate change and land use can help identify which ecosystems require protection and which areas require urgent conservation/restoration.

Paleoecological records provide reliable ecosystem baseline data for setting conservation, restoration, and management goals (Wingard et al. 2017). This is because paleoecological datasets describe ecosystem patterns and processes over centuries and millennia, which can then be used to develop effective frameworks and strategies for ecosystem interventions (Wingard et al. 2017). However, current baseline data are insufficient in Nigeria to contextualize the long-term regional ecosystem patterns in response to past changes in climate and land use (Eneh 2011). Adeleye et al. (2021a) have used paleoecological datasets to detail the temporal magnitude of vegetation compositional change (turnover) in Nigeria and surrounding western African regions over the last 10,000 years in response to past changes in climate and land use. Here, we compare past turnover in forest and savanna with current rates of change and highlight what the differences mean for ecosystem restoration in the country. To understand the history of present-day ecosystems, we examined Holocene datasets spanning the last 7000 years.

Magnitude of change in Nigeria's forest and savanna

Adeleye et al. (2021a) found that vegetation in many areas of western Africa, including the sites indicated in Figure 1, experienced accelerated turnover in the last 7000 years in response to both climate change and intensified land use. Focusing on records only from Nigeria, savanna in northern Nigeria experienced the overall greatest turnover in the last 7000 years; in contrast, forests in southern Nigeria were relatively stable prior to 2000 years ago (Fig. 2a). A significant ($p < 0.05$) link between savanna turnover and changes in rainfall and temperature suggests long-term sensitivity of savanna to past climate change, with greatest turnover occurring after the termination of the African Humid Period around 6000–5000 years ago, when conditions became drier and cooler than before. The fact that forest showed little turnover in response to these decreases in precipitation and temperature suggests that forests exhibited long-term resilience (minimal changes in species composition) to past climate changes (Fig. 2a-c). It is also possible that the exploitation of northern Nigerian savanna for food production from ~3400 years ago contributed to rapid changes in savanna composition during this period (Kay et al. 2019). Food production expanded in southern Nigeria from ~2200 years ago and would have also contributed to high forest turnover in the last 2000 years (Kay et al. 2019).

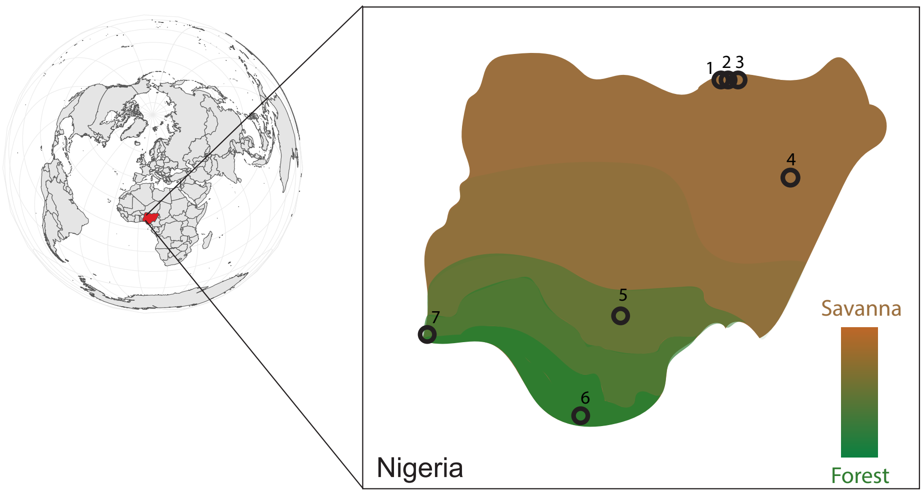

Figure 1: A generalized representation of vegetation distribution in Nigeria and site locations of pollen records used in this article (black circles). Savannas (brown) include Sahel, Sudan, and Guinea types. Forests (green) include lowland rainforest, deciduous forest, freshwater swamp forest and mangrove forest. Pollen records spanning the last 7000 years include Bal Lake (1), Jikariya Lake (2), Kajemarun Oasis (3), Tilla Lake (4), Ohe Pond (5), Ofuabo Creek (6), and Badagry Creek (7). See Adeleye et al. (2021a) for more details regarding the pollen records.

Arid to semi-arid terrestrial ecosystems have been identified as susceptible to future climate changes (Watson et al. 1997), and increases in temperature and declines in rainfall have been predicted for northeastern Nigeria (Shiru et al. 2020), where most of the savanna pollen sites are located (Fig. 1). Our paleoecological results show that Nigeria's savanna was sensitive to past rainfall declines after the end of the African Humid Period when the climate was also becoming cooler (Fig. 2b-c). This drought promoted grassland communities (Adeleye et al. 2021a). Considering the current impact (desertification) of warm, dry conditions in Nigeria's savanna (Olagunju 2015), projected climate change will likely intensify drought and its impacts (e.g. species mortality, longer recovery time, shifts in species range) on both grassland and non-grassland communities, leading to further desertification (Sankaran 2019). The increasing trend of intensive agriculture in northern Nigeria may also exacerbate the impact of climate change by suppressing native species recovery after extreme drought events/episodes. This combination seems likely to cause the savanna to enter novel states with greater turnover than anything that has been observed in the last 7000 years (Sankaran 2019; Olagunju 2015).

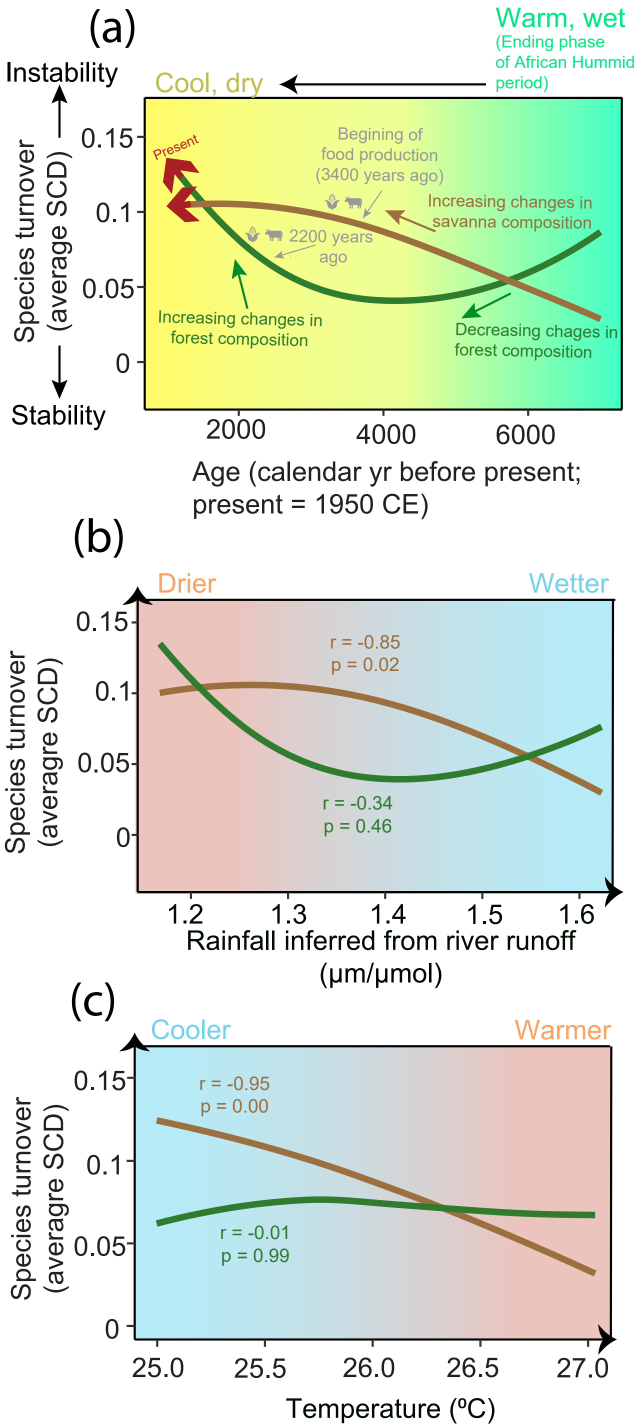

Figure 2: (A) 7000-yr record of plant species turnover (average Squared Chord Distance (SCD) between adjacent pollen samples) in northern Nigerian savanna (brown line) and southern Nigerian forest (green line) in relation to past changes in climate and land use (adapted from Adeleye et al. 2021a and Kay et al. 2019). SCD is a measure of dissimilarity between samples (pollen spectrum). **(B, C)** Smoothed curves of turnover-climate relationships, with correlation test results. See Adeleye et al. (2021a) for climate data sources, and Adeleye et al. (2021b) for details on SCD calculation.

In contrast to earlier time periods, the last two millennia show highest species turnover in forests, compared to savanna (Fig. 2a). This agrees with modern vegetation mapping and surveys in Nigeria by Abbas et al. (2018), which indicate that forest ecosystems are rapidly changing, and shrinking faster than savanna at 9% and 4%/yr, respectively. Climate change may contribute to recent forest turnover in Nigeria, but the stability of the forests over the last 7000 years in the face of cooling and drought likely indicate that humans were responsible for forest decline and secondary-forest regrowth, especially in the last 2000 years (Kay et al. 2019). Human population density is currently highest in southern Nigeria in rainforest areas, and poverty-related agricultural practices, logging, mining, pollution, and urbanization are known to be causing forest loss and degradation in the region (Abbas et al. 2018; Fasona et al. 2018). Human impacts have likely resulted in major changes in forest composition in southern Nigeria (Fauset et al. 2012), and growing human population pressure will only further exacerbate biodiversity loss and widespread forest replacement through the introduction of novel anthropogenic vegetation.

Implications for ecosystem restoration in Nigeria

The results derived from paleoecological data presented here provide an understanding of long-term resilience and sensitivity of Nigeria's vegetation to drought and human impacts, and this information can assist us in identifying areas of restoration and conservation priority in the country. Our results suggest that recent human land use, rather than natural climate variations, has caused the greatest changes that the southern Nigerian forests have experienced in the last 7000 years. Therefore, effective forest conservation strategies will necessarily involve priority protection from deleterious human land use, especially agriculture, logging, and industrialization, to maintain/increase resilience in existing forest reserves and restore resilience in affected areas. Conversely, climate-sensitive savannas in northern Nigeria should be closely monitored for warning signs of climate-change impacts. Slowing down the rate of savanna transformation may require more complex and carefully designed ecological strategies that go beyond the reduction of intensive agriculture, to consider the high sensitivity of the ecosystem to drought. For instance, conservation strategies should involve a good understanding of savanna ecosystem dynamics across multiple temporal and spatial scales in savannas (Osborne et al. 2018). In addition, any management actions in Nigeria need to take into account their potential impacts on local stakeholders, since conservation gains cannot be sustainable if they come at the cost of human livelihoods.

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doi.org/10.22498/pages.30.1.30

Challenges to forest restoration in an era of unprecedented climate and wildfire activity in Rocky Mountain subalpine forests

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Unprecedented conditions in Rocky Mountain subalpine forests challenge contemporary approaches to forest restoration, requiring deep thinking across the science–management spectrum. Paleoecology can contribute to this endeavor by contextualizing ongoing change and revealing how ecosystem transformations unfolded in the past.

Fire and anthropogenic climate change in Rocky Mountain subalpine forests

Anthropogenic climate change is enabling increased fire activity across western North American forests by increasing fuel aridity (Abatzoglou and Williams 2016). Fire intensity and spread in dry fuels is more extreme, especially in high-wind conditions, evading fire control and often resulting in greater human and ecological impacts.

The pattern of increased burning is particularly evident in subalpine forests of the western US (Alizadeh et al. 2021). Subalpine forests are high-elevation, conifer-dominated ecosystems that span the ca. 1000 m just below treeline, across the Rocky Mountains. Wildfires have shaped subalpine forests for millennia, but emerging interactions among climate, fire, and society are transforming these fire-prone social-ecological systems.

Historically, fire in subalpine forests was limited by high fuel moisture and only occurred in unusually warm, dry conditions, with mean fire-return intervals of one to several centuries (e.g. Higuera et al. 2021). Contemporary climate change is promoting fire in subalpine forests by increasing the frequency and intensity of drought, making fuels dry enough to burn more frequently (Alizadeh et al. 2021).

Uncharted territory: subalpine forests now burning more than any time in recent millennia

After extraordinary burning across the western US in 2020 (Higuera and Abatzoglou 2021), we suspected that climate change may have pushed contemporary burning beyond the longstanding range of variability experienced in some Rocky Mountain subalpine forests.

We tested this hypothesis using a unique network of 20 paleofire records within a 30,000-km^2 study region in northern Colorado and southern Wyoming. We found that subalpine forests in the 21st century are now burning twice as often as they have over the past two millennia: estimated mean fire return intervals are now 117 yr compared to an average of 230 yr over the past two millennia (Fig. 1; Higuera et al. 2021). Additionally, the 21st-century rate of burning (e.g. area burned per unit time) is over 20% higher than the maximum rate estimated over the past two millennia, which occurred during the early Medieval Climate Anomaly (MCA; 770 to 870 CE), when Northern Hemisphere temperatures were ~0.3°C above the 20th-century average (Mann et al. 2009). The paleofire record thus highlights that 21st-century climate change has enabled fire activity that exceeds the range of variability that shaped these ecosystems for millennia (Fig. 1). We are clearly in uncharted territory.

Core insights from paleoecology in Rocky Mountain subalpine forests

The rich network of paleorecords in Rocky Mountain subalpine forests, including climate, fire, and vegetation histories, highlight three themes relevant to understanding contemporary change and informing forest-management decisions.

First, fire itself is not novel in these systems; rather, it is the frequency of burning that is unusual. For millennia, subalpine forests experienced high-severity wildfires—killing most trees—once every one to several centuries. Holocene pollen, geochemical, and charcoal data indicate that vegetation and ecosystem properties recovered in the decades after wildfire, exhibiting resilience to individual fire events (Minckley et al. 2012; Dunnette et al. 2014).

Second, paleorecords bolster our contemporary understanding of the climate controls of fire in subalpine forests. Tree-ring research reveals widespread burning during years of unusually warm, dry conditions in Colorado subalpine forests (Sibold and Veblen 2006), and lake sediments studies from the same region show that fire activity varies with centennial-scale climate variability (Calder et al. 2015; Higuera et al. 2021; Fig. 1).

Finally, the paleorecord reveals just how rarely wildfires caused state changes in the past, in subalpine forests and beyond (e.g. Crausbay et al. 2017), mainly when changes in climate and fire jointly drove ecosystem transformation. For example, extensive burning in northern Colorado during the MCA transformed some subalpine forests to "ribbon forests", narrow bands of trees separated by subalpine meadow communities. This lower tree density and forest extent was maintained afterwards by snowier conditions of the Little Ice Age (ca. 1400–1700 CE, Mann et al. 2009), and still persists today (Calder and Shuman 2017).

With 21st-century climate change accelerating beyond the bounds of the past, we

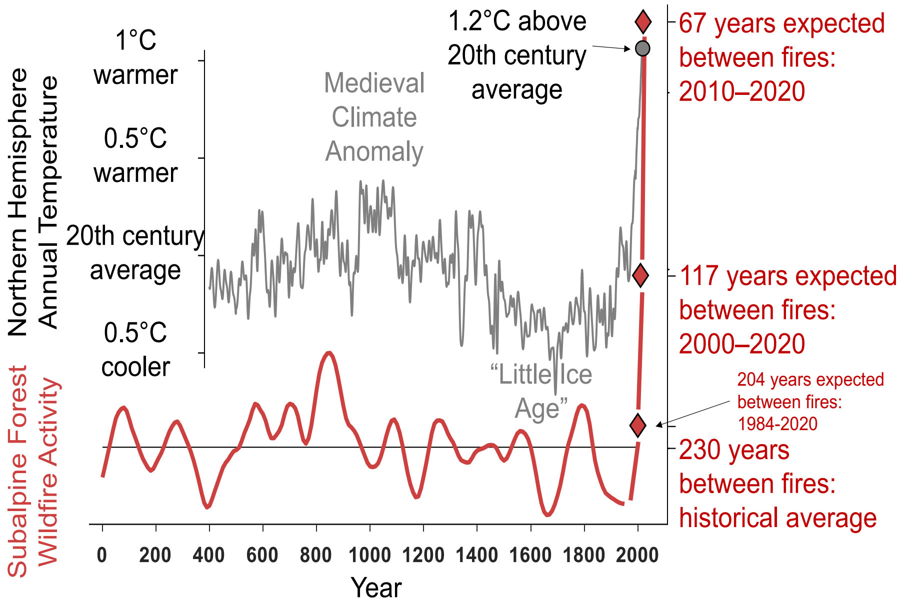

Figure 1: Northern Hemisphere climate history (from Mann et al. 2009) and subalpine forest-fire history from 20 lake-sediment records spanning a 30,000-km^2 region in northern Colorado and southern Wyoming (Higuera et al. 2021). The red line reflects the fire rotation period, equivalent to the average time between fires at any one lake, or mean fire return interval. Red diamonds reflect contemporary burning in the study region. Figure reused under CC license from TheConversation.com, modified from Higuera et al. (2021).

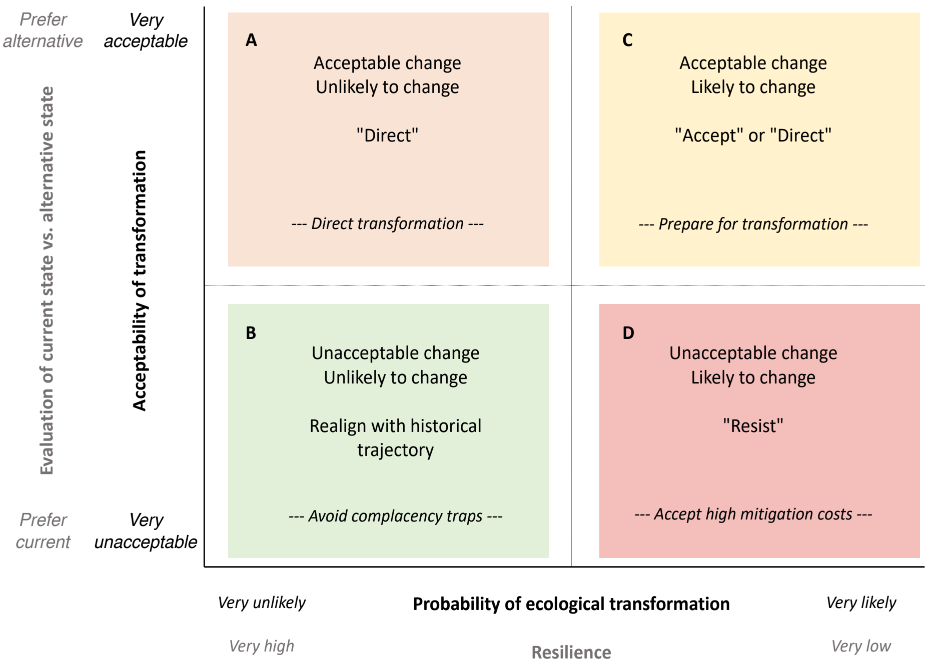

Figure 2: Managers face challenges that require understanding both the probability of ecological transformation and the acceptability of such changes. The "resist, accept, direct" framework can help decision making when transformation is **(C, D)** likely or **(A)** desirable; when transformation is **(B)** unlikely and undesirable, restoration goals remain appropriate and feasible. Modified from Higuera et al. (2019).

expect that events that were exceptional in the paleorecord will become increasingly common, altering the trajectory of ecosystems and their longstanding resilience to wildfires.

Challenges to ecological restoration

Climate change and increased area burned across western US forests adds urgency to the need for ecological restoration in many ecosystems. Ecological restoration is defined as the "process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Society of Ecological Restoration (SER); ser-rrc.org/what-is-ecological-restoration). While the concept of recovery is central, the goal is to "return a degraded ecosystem to its historic[al] trajectory, not its historic[al] condition" (emphasis added). The emphasis on trajectories acknowledges non-stationarity (e.g. past climate variability), orienting restoration targets towards what an ecosystem would be like today in the absence of past degradation, damage, or destruction.

The goal of restoring past dynamics and trajectories is clearly applicable to many low-elevation forests across the western US, which, unlike subalpine forests, historically burned frequently in low-severity surface fires (e.g. mean fire return intervals < 10-50 yr). In these forests, fire suppression, policies preventing Indigenous fire stewardship, and high-grade logging since the 19th century have altered forest structure and composition (Hessburg et al. 2019). Restoration efforts here thus focus on reducing tree biomass and retaining thick-barked, fire-resistant species that dominated prior to fire suppression, to help ultimately reintroduce and sustain frequent low-severity fires.

Similar changes in tree density and composition are not as prevalent in subalpine forests, due to their historically long fire-free intervals (Fig. 1) and more limited land uses. Yet, contemporary climate change is increasingly altering disturbance regimes and ecological trajectories in these forests beyond the historical range of variability, even in the absence of past damage or degradation (Turner et al. 2019; Higuera et al. 2021). The combination of increased burning and warmer, drier post-fire conditions in subalpine forests requires a management framework that is more forward-looking in time, relative to the goal of ecological restoration.

Navigating uncharted territory

In a world experiencing rapid climate change, realigning ecosystems with historical trajectories may be inconsistent with expectations of climate-driven ecological change. The resist-accept-direct (RAD) framework has been developed to guide natural resource management when ecological transformation is likely (Schuurman et al. 2022). The RAD framework identifies three management responses to ecological transformation: resist, accept, or direct ecological trajectories. This adds options to the restoration-oriented goal of realigning systems with historical trajectories (Fig. 2). Paleoecology provides the long lens needed to contextualize contemporary ecological trajectories, and help inform choices among different RAD options if transformation is inevitable.

For example, the combination of climate change and increased burning in subalpine forests, now outside the range of variability in our study area (Fig. 1), suggests the likelihood of fire-catalyzed ecological transformation is high. Are there areas where dispersing seeds or planting seedlings in high-severity patches would help managers resist future forest loss, given reduced natural tree regeneration under warmer, drier conditions? Would planting different species help *direct* the ecological trajectory to a new community, with trees better adapted to future conditions? Or, are managers and stakeholders willing to accept the post-fire ecological trajectory, yet unknown and possibly novel, with minimal intervention?

Deciding among RAD options is complex and multidimensional, because consequences are social, cultural, and institutional, as well as ecological. Science that provides a better understanding of the likelihood of ecological transformation (i.e. *x*-axis in Fig. 2) is an important starting point for RAD decision-making (Crausbay et al. 2022), but assessing the acceptability of change (i.e. *y*-axis in Fig. 2) requires community input and extends beyond the science of ecology (Higuera et al. 2019).

Conclusions

Paleoecology is particularly well poised to inform RAD decision-making because the long historical perspective can help assess if, and when, contemporary conditions are unprecedented, and, thus, if transformation is likely. Paleoecology also offers opportunities to learn from past ecological change (Nolan et al. 2018), and hone in on the triggers, rates, and ecological trajectories that characterize the process of transformation. Integrating paleoecological knowledge with processes for making RAD decisions will be increasingly relevant when ecological restoration is not possible.

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doi.org/10.22498/pages.30.1.32

Sociological analysis of the PAGES network

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In 2021, PAGES celebrated 30 years of intense activity building and managing a global scientific network to study past environmental and climate change. For this, PAGES partnered with the Maison des Sciences de l'Homme et de l'Environnement Claude Nicolas Ledoux (CNRS, Université de Franche-Comté, Besançon, France) to host a masters student in sociology, who analyzed many aspects of the PAGES program since its creation in 1991, in terms of its organization, its scientific objectives, and the epistemological strategies used.

The material collected and studied during the internship includes a selected excerpt from PAGES publications and archives, and five interviews with PAGES officials. The documentary corpus was selected to cover the longest possible period of time to obtain a total volume of text to be studied that was manageable within the three-months internship. This corpus consisted of: (1) all the editorials of Past Global Changes Magazine since the publication of the first issue in 1993, and (2) all the "science plans" defining and redefining the scientific directions of the program. Interviews were conducted with three former executive directors (Frank Oldfield, Keith Alverson, and Thorsten Kiefer), the current executive director (Marie-France Loutre), and a member of the scientific steering committee (Emilie Capron). These interviews allowed us to better understand how the scientific policy of PAGES was implemented.

The study shows that over the past 30 years, the researchers who have carried out their work in the PAGES program, regardless of their discipline, are first and foremost recognized in their efforts in developing multiple forms of "circulation" between knowledge, skills, and data. Circulation is a modality of knowledge production within scientific disciplines (or between disciplines) in which the progress of scientific understanding depends on the comparison of singular cases that are never completely reducible to each other (Ogorzelec-Guinchard 2021).

The first form of circulation is found in the highly heterogeneous, yet complementary, nature of the data and proxies used to study past global change. The second form of circulation covers the spatial dimension of research. To understand the functioning and dynamics of the climate system, it is necessary to collect and articulate data from all regions of the world, even if each region remains marked by its own particularities.

A third form of circulation, between observations and models, characterizes the research within PAGES. This form of circulation can be two-way, seeking either the interpretation of data through a functional model, or a "path of reference" (Latour 1995), returning to the field where the data were collected, to apply a predictive model. Finally, the "paleo" approach is characterized by a temporal circulation of knowledge between past and present. This fourth form of circulation offers a perspective on contemporary climatic and environmental changes by placing them in historical context to make them more intelligible.

The originality of the PAGES project lies in these multidimensional exchanges, stemming from all the circulations, likely to bring out new ways in which societies think about their relationship to time, and to analyze how societies settle and unfold in time, especially in times of crisis (Hartog 2015). PAGES' aim is to reorder our experience of time to better understand contemporary changes, the role of societies in these changes, the climatic and environmental mechanisms at play, and to reduce the uncertainties associated with future projections as much as possible.

The forms of circulation (Fig. 1) discussed above are based on the ability of researchers to move between varied geographical and temporal contexts, and sometimes between very specific skillsets and disciplinary approaches. Bringing researchers from different scientific cultures together within working groups and around the same problem forms an arrangement of "distributed cognitions" (Hutchins 1995) and a network of intelligence. Studies of the interactions between natural systems and social systems certainly call for the expansion of these working groups and networks, and for a better understanding of how to manage them.

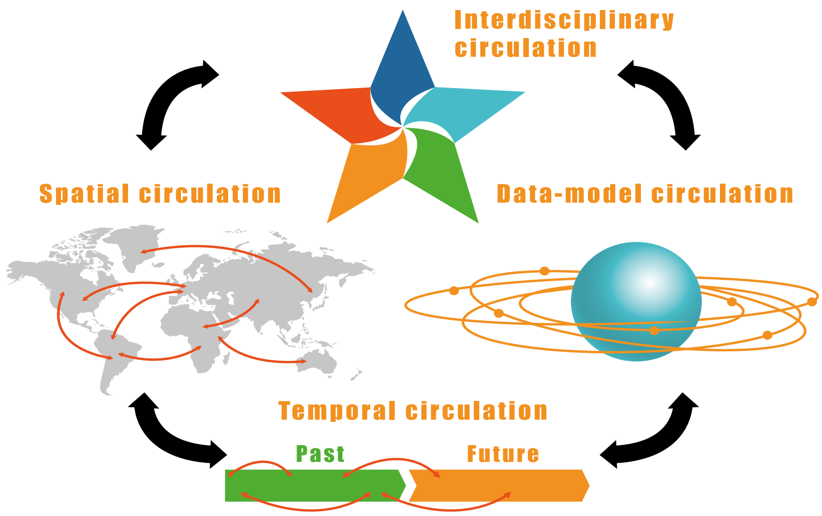

Figure 1: Forms of circulation identified and promoted within the PAGES network.

The ability to create bridges between many different experiences and disciplinary concepts is akin to creating new neural connections that can lead to the emergence of real and original knowledge. As one of the former directors of the program put it: "*My own experience was actually: if you go to a workshop, and you are exposed to other people, other ideas, other perspectives – provided that they are well communicated, so you understand something – as this is very inspiring. And I heard this million times of people feel inspired. Purely by being exposed to something new builds new synapses.*"

Finally, an extension of these types of circulation outside the paleo network is expressed in the dissemination of scientific works resulting from all of PAGES' activities to the wider academic world, and beyond. The interviews conducted showed that this extension, which consists of exchanges with actors outside the network, should be a priority for the researchers. This transfer deserves to be a priority, because it is through this knowledge exchange with the non-academic world, public and decision-makers, that the research objectives are enriched and made more meaningful.

The full report from this internship (in French) can be accessed at pastglobalchanges.org/publications/128532. We do not claim to have thoroughly analyzed PAGES' history, but this report sheds light on the challenges that have been faced by the PAGES program over the last 30 years. PAGES, in stimulating and facilitating these different forms of "circulation", responds effectively to the scientific and political challenges posed by the environmental and climatic crisis we are currently experiencing.

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doi.org/10.22498/pages.30.1.33

Socio-ecological approaches to conservation

Daniele Colombaroli[1] and Evan Larson[2]

The recent UN Climate Change Conference in Glasgow (COP26) highlighted key priorities for supporting climate mitigation goals and strengthening policies on adaptation to future climate changes (UNFCCC 2021). In particular, the Glasgow Leaders' Declaration on Forests and Land Use pledged the conservation and sustainable management of forests, with the primary goal to end deforestation by 2030 (Glasgow Leaders' Declaration 2021).

Such ambitious initiatives highlight the urgent need for more sustainable land-use practices to avoid disastrous ecological losses. Challenges emerge, however, from conflicts between conservation targets and socio-ecological and environmental needs (Colombaroli et al. 2019). For example, traditional land stewardship among many Indigenous cultures includes the intentional use of fire to enhance biodiversity and reduce fire risk (Lake and Christianson 2019). Yet, these practices have been curtailed over decades by fire exclusion, monoculture afforestation and other practices, often justified by a pervasive "myth" of wilderness held in many western societies (Mariani et al. p. 34). Conservation plans shaped by this myth often lack the knowledge base to reconcile set restoration targets and traditional use by local communities (Berkes 2004). Through ongoing processes of colonization, this often results in the exclusion or eradication of Indigenous cultures locally, with traditional practices rarely considered for landscape conservation (Johnson et al. p. 36).

Addressing future conservation challenges will require more holistic approaches that weave together the best scientific understanding and the wisdom of Indigenous knowledges (Mistry and Berardi 2016). In this issue, we present regional case studies showing how complex conservation challenges can be addressed through the integration of western scientific methods that inform on landscape transformations over time (paleoecology, dendroecology, and archeology), and diverse knowledge systems (Indigenous and Traditional Knowledges; Fig. 1). Merging such diverse approaches may help western thinking to better recognize the role of humans as vital parts of ecological systems, and move toward approaches to management based on reciprocal understanding, rather than the false divide between humans and nature (Caillon et al. 2017).

For example, sediment proxy records in the Mediterranean show how pastoral fires maintained a cultural landscape mosaic of high biodiversity values and lower fire risk over centuries (Coughlan et al. p. 38). In North America, fire-scarred trees serve as biocultural artefacts that provide evidence of the long-lived legacy of human connections to place, and the associated influence of fire that lingers on present landscapes (Johnson et al. p. 36). In South Africa, sediment records illustrate how local communities were highly dynamic and responsive to environmental variability, and how their responses reflected local conditions and resources (Razanatsoa and Gillson p. 40). Archeological and paleorecords in Ireland highlight the long-term spans of people-landscape interactions that shaped ecosystems in a national park (Hawthorne et al. p. 42). Such integrated knowledge reinforces the notion that people have been an integral component of landscapes for millennia, stewarding landscapes over generations, and shaping (and being shaped by) environmental variability. These cultural practices and local adaptations offer models for the maintenance and restoration of resilient landscapes (Kulkarni and Bhaskar p. 44), a crucial step in light of future climate change impacts on ecosystems (Lestienne et al. p. 46).

A recognized challenge exists for identifying best practices for researchers to engage with Indigenous communities and Traditional Knowledges, without furthering the extractive and exploitative relationships perpetrated by western societies for centuries (Copes-Gerbitz et al. p. 48). Conservation priorities set by agencies often fail to acknowledge the significance of local traditions, which often reside outside of conventional Western academic disciplines (le Grange 2004). Efforts to reshape these relationships are growing, such as the GBP 1.7 billion pledge at COP26 to support Indigenous peoples and local communities for more sustainable and effective management. A framework for these efforts is presently lacking (de Freitas et al. p. 50), but clearly this is an area of need.

New integrative, cross-disciplinary evidence is urgently needed to support a more holistic understanding of such complex issues built through dialog between ecological and socio-cultural disciplines, traditionally separated in academia. The science highlights included in this *PAGES Magazine* issue provide examples of how integrative socio-ecological approaches can help close the gap between disparate disciplines, while helping to bridge understanding between western scientists and Indigenous peoples. This is a primary goal of the PAGES DiverseK working group (pastglobalchanges.org/diversek), which aims to better address conservation challenges that are continuously "moving targets" in the context of ongoing rapid climate and ecosystem changes.

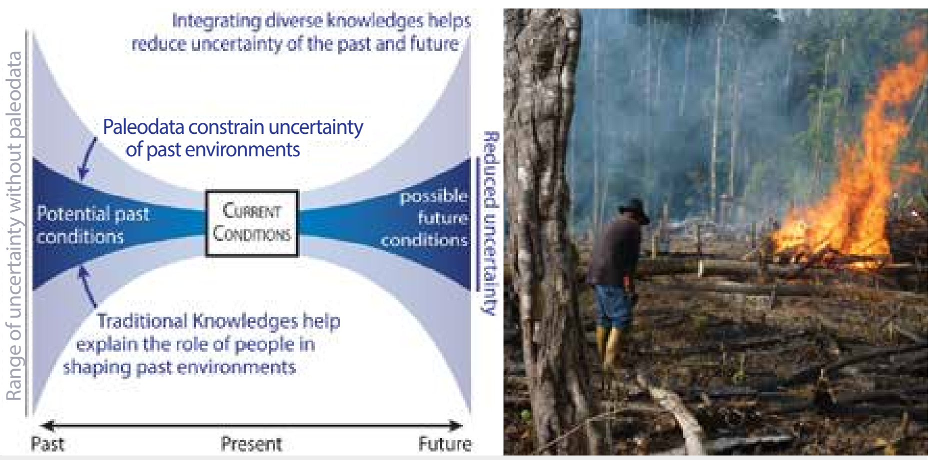

Figure 1: Left: Integrating diverse knowledge systems reduces uncertainty about past environmental conditions and how they were shaped through traditional land-use practices and relationships with the land, thereby enabling improved understanding of the range of future potential conditions and how we might engage in environmental stewardship to guide future change. Right: An example of traditional use of fire in Venezuela for shifting cultivation (photo credit: Bibiana Bilbao).

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doi.org/10.22498/pages.30.1.34

Higher fuel loads and more fire follow removal of Indigenous cultural burning across southeast Australia

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The current wildfire crisis in southeast Australia is unprecedented. The transition from Indigenous to colonial land management since 1788 has resulted in a build-up of woody fuels, which, in combination with climate change, has resulted in more extreme bushfires.

The present: unprecedented wildfires
The Australian "Black Summer" bushfires in 2019/2020 have been part of a series of recent wildfires that have attracted global media coverage and scientific interest. This event had significant immediate and ongoing financial costs, and a series of disastrous environmental consequences. With ca. 18 million hectares burned, the 2019/2020 event represents the worst fire season in the recorded history of southeast Australia thus far. Nine times more forest and woodlands burned in this single fire season than in the previous 17 years combined (Bowman et al. 2020). This event is an example of how the compounded effects of climate change and urban expansion are increasing fire impacts to levels unmatched in recorded history (Bowman et al. 2017).

The catastrophic bushfires in Australia exhibit a similar pattern of increasingly severe wildfires recorded in British Columbia (2017), California (2018, 2020), and the Amazon (2019). These regions were long managed by Indigenous peoples through cultural burning and were then subsequently invaded and colonized by Europeans who implemented different land management practices, including fire suppression. Following this transition, cultural burning was often banned or suppressed in the subsequent centuries, which has had important consequences for fire regimes and the ecosystems in which they operated.

In the wake of these events, researchers and policymakers have been urged to address questions about future land and fire management by including the legacy of historical burning on present landscapes. For example, much attention has been directed towards traditional landscape management's implications for bushfire mitigation, and how past landscapes were managed throughout the millennia before British invasion and colonization of Australia (Steffensen 2020). It is imperative that we understand how landscapes have changed under different management techniques (Indigenous vs. post-colonial). Such knowledge can be provided by paleoecological studies, which can offer a unique and unbiased view of this critical issue.

The past: changes in land cover and fire since colonization in southeast Australia
Indigenous people have inhabited the Australian continent for at least 65,000 years (Clarkson et al. 2017). Before British colonization in 1788 CE, Indigenous people managed Australia's flammable vegetation using long-standing firing practices called "cultural burning" (Gott 2005). This management shaped the balance between herbaceous and woody biomass, limited shrub density in understorey vegetation, and maintained patchy, open woodlands and savanna-like vegetation (Gott 2005; Gammage 2011). This management occurred across a broad altitudinal gradient. Due to limited ground-to-crown connectivity and fuel abundance, this managed landscape was less prone to destructive fires than current forests (Gott 2005). In contrast, British colonists managed land through deforestation and intense firing to clear areas deemed suitable for farming (e.g. low-elevation plains). However, forests in unsuitable areas (high-elevation or rugged terrain) were left unmanaged or exploited through selective logging for firewood or timber (Griffiths 2001).

Currently, there is a vast array of evidence for sophisticated, Indigenous cultural burning practices, as provided by oral tradition, historical, and ethnographic sources (Gott 2005; Gammage 2011; Pascoe 2014). The latter depict much of the southeast Australian pre-colonial landscape as open and grassy, with scattered trees and shrubs (Gammage 2011 and references therein). However, empirical evidence is scant, and a consensus in the scientific community is lacking. We carried out the first regional-scale scientific assessment of the land-cover and fire activity change before and after British colonial settlement of SE Australia (Mariani et al. 2022). This new work presents an integration of novel pollen-based land-cover reconstructions (REVEALS modeling; Sugita 2007) and fire histories.

Our land-cover reconstruction of SE Australian vegetation shows that pre-colonial landscapes were predominantly grassy, with low tree cover (14% on average), consistent with a savanna-like environment at the regional scale. Our findings agree with the long-neglected, cultural knowledge of Indigenous people and corroborate historical records, including early settlers' diaries and artworks. These findings contrast with previous interpretations based on unmodeled pollen results, which grossly overestimated past tree cover across the region (Mariani et al. 2022). Since colonization, shrub cover increased across much of the SE Australian region, thickening the understorey of forests and woodlands (Fig. 1a; Mariani et al. 2022).

Long-term fire history reconstructions demonstrate that fire has long been present in the Australian landscape, deeply intertwined with climatic change and Indigenous cultural practices (Kershaw et al. 2002; Mooney

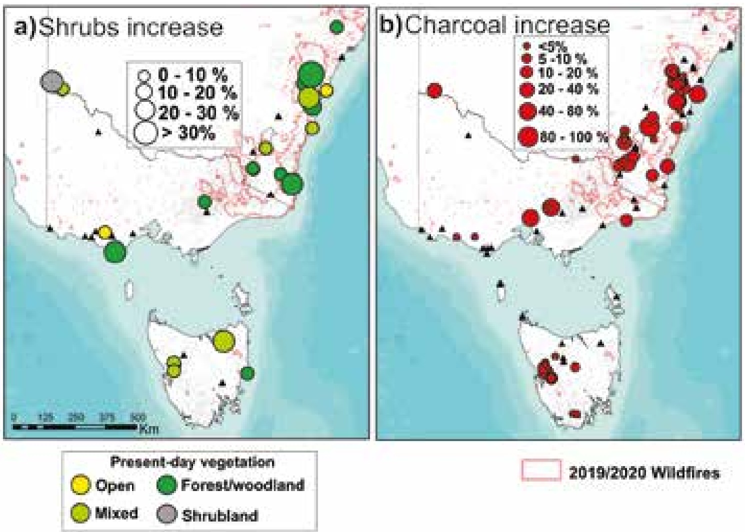

Figure 1: Map of Southeast Australia showing sites with a positive percent increase in **(A)** shrub cover and **(B)** charcoal influx following British colonial settlement post-1788 CE (modified from Mariani et al. 2022). Shrub cover and charcoal increases are evident in forest/woodland areas along the coast of SE Australia, where the 2019/2020 fires had the most extreme impacts (pink outline). Sites showing no increase in **(A)** shrubs or **(B)** charcoal are shown as black triangles.

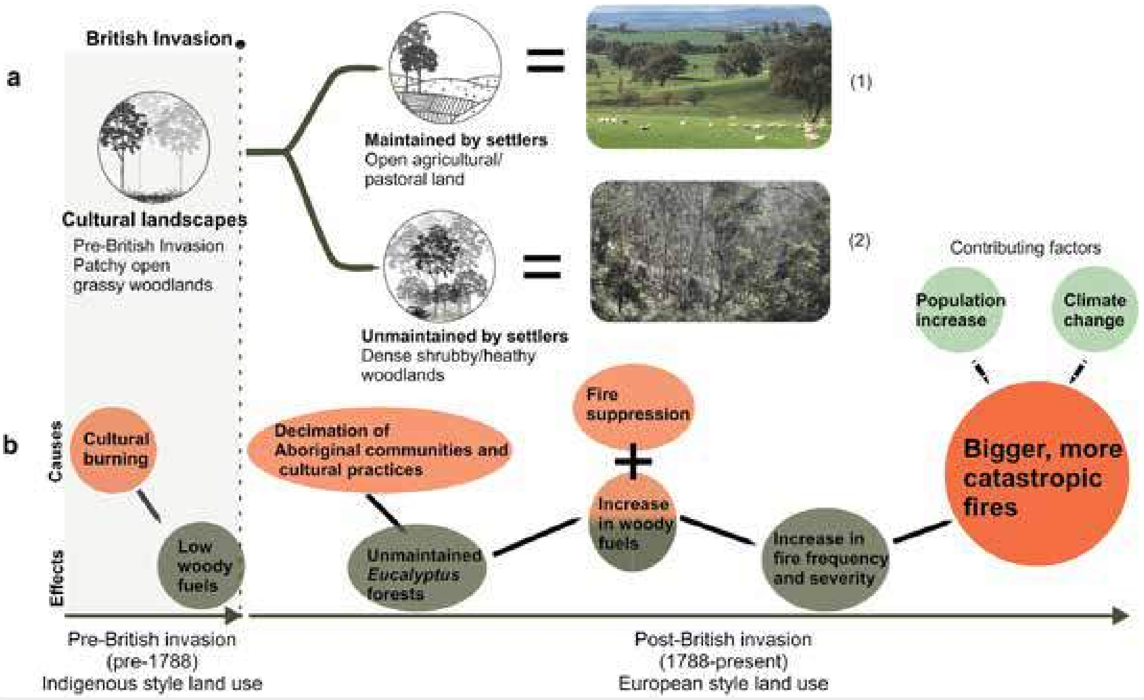

Figure 2: Summary diagram showing **(A)** the diverging trajectories of Southeast Australian landscapes following colonial settlement; **(1)** areas maintained by settlers for farming purposes; **(2)** areas not maintained by settlers undergoing an increase in shrub cover (Mariani et al. 2022); **(B)** trajectory of change in forests/woodlands since British invasion (reproduced from Fletcher et al. 2021a).

et al. 2011). The consistent occurrence of charcoal in sediments prior to 1788 (Mooney et al. 2011) indicates that fire was an almost universal feature of the southeast Australian landscape. After British colonization, we detected a substantial increase in biomass burned across most areas, especially within woodland/forest (Fig. 1b). This recent increase led to biomass burning levels exceeding levels in the Holocene record (Mariani et al. 2022; Mooney et al. 2011).

Fire's increase after colonial settlement has multiple non-exclusive causes: (1) disruption of Indigenous burning, which would have promoted the accumulation of woody biomass conducive to more intense bushfires; (2) post-colonial firing practices targeted at the removal of woody biomass for land clearance in areas deemed suitable for agriculture according to European standards; and/or (3) recent climate change favoring dryness of fuels and biomass accumulation through CO_2 fertilization.

Paleodata help refine this list of possible causes. Our land-cover and fire activity reconstructions indicate divergent trends in different land-use areas (open vegetation areas vs. forests/woodlands), with open vegetation areas displaying a decrease in woody cover following colonial settlement, while an increase in woody fuels occurred in forests/woodlands. This suggests that management practices, rather than the spatially consistent influences of regional climate, are likely to blame for the increase in fire. Indeed, the greatest post-colonial shrub increase occurred in the forest/woodland zones most affected by the 2019/2020 wildfires (Fig. 1a). While extreme fire-weather driven by climate change was responsible for fuel dryness during this event (Nolan et al. 2020), we suggest that the increased volume and connectivity of woody fuels, due to shrub encroachment following the cessation of cultural burning, has raised wildfire risks to unprecedented levels (Fig. 2).

The future: restoring Indigenous fire management

Following the unprecedented 2019/2020 wildfire event, some researchers and policymakers have advocated for the return and expansion of Indigenous cultural burning practices to mitigate climate-driven catastrophic wildfires. However, there are various barriers to the effective reinstatement of Indigenous fire management in SE Australian forests. For example, there is some uncertainty about the degree to which Indigenous people managed high biomass and extremely flammable *Eucalyptus* forests (77% of Australian total forest area) prior to 1788. Researchers at the University of Melbourne and the Australian National University, under the guidance and inspiration of local Indigenous communities, are currently collecting high-resolution data from targeted forest areas within SE Australia through the Discovery Indigenous Australian Research Council (ARC)-funded project, PF-FIRE (Past Fire Frequency and Intensity Reconstructions; pf-fire.science.unimelb.edu.au).

A related issue is the myth of "wilderness" areas, which are depicted as uninhabited, free from past human agency, that attract visitors globally. This affects public perceptions, and influences land-management decisions in colonized lands, neglecting Indigenous people's agency on the landscape (Fletcher et al. 2021b). SE Australian forests and woodlands cannot be defined as ''wilderness'', as they have been the homelands of Indigenous Australians and, as such, cannot be conceptualized in dualistic "nature vs. culture" terms. This dualistic thinking has underpinned land management and created legal barriers that prevent Indigenous people from efficiently and effectively managing their lands. For more effective land and fire management, Indigenous people must be engaged in all stages of scientific research and the development of policies and practices aimed at mitigating extreme bushfires in southeast Australia.

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doi.org/10.22498/pages.30.1.36

Blending tree-ring fire-scar records and Indigenous memory in northern Minnesota, USA

Lane B. Johnson[1], E.R. Larson[2], K.G. Gill[1] and J. Savage[3]

Tree-ring records of frequent fire in northern Minnesota are increasingly recognized as eco-cultural phenomena. Indigenous perspectives provide the cultural context to reinterpret tree-ring fire-scar records in ignition-limited systems like the Upper Great Lakes Region.

People in the fire environment of the Upper Great Lakes Region

Ideal environmental policy represents a synthesis of ecological knowledge, diverse values, and cultures that guides collective action toward balanced outcomes. Achieving this ideal may seem daunting, but lessons for Western scientists provided by paleoecological records are increasingly clear in how best to pursue it: *listen*. Quantitative environmental history derived from proxies like charcoal, pollen, and tree rings illustrate the *what* of history; engaging with Indigenous knowledge systems is how researchers might better understand the *why* of history. Such is the emerging case of fire history research at the University of Minnesota Cloquet Forestry Center, USA, where the tree-ring record of frequent fire (what) is being re-examined as an eco-cultural phenomenon (why).

The vegetation communities of the Upper Great Lakes Region of North America assembled over millennia following the recession of continental ice sheets. Two factors were part of this process since time immemorial: fire and people. For the last 12,000 years people have been an integral component of fire-shaped landscapes, influencing when and where fires burned. Indigenous people modified vegetation conditions over generations, reinforcing and accentuating landscape patterns through the intentional application of fire long before Euro-American colonization reshaped fire dynamics to a largely fire-excluded state. Here, we report on part of a growing network of tree-ring-based fire-history sites in the Upper Great Lakes Region to convey how a cross-cultural perspective better explains the causes of frequent fire in forest ecosystems widely considered to be ignition-limited (Balch et al. 2017).

Indigenous land with University of Minnesota presence since 1909

Nagaajiwanaang, the Reservation of the Fond du Lac (FDL) Band of Lake Superior Chippewa – known as Anishinaabe/g [sing./plural], meaning the "original people", and part of a group of culturally affiliated tribal communities in the Great Lakes region of North America – was established through the 1854 Treaty of La Pointe and opened to Euro-American colonization by the United States government in 1905. Through the contentious process of allotment, "excess" Anishinaabe land was sold to Euro-Americans, advancing the encroachment of white colonizers on lands once held collectively by the FDL Anishinaabe (Akee 2020). The University of Minnesota Cloquet Forestry Center (University forest) is one example of the 86 million acres of Indigenous lands removed from collective ownership between 1905 and 1909 in the United States (Catton 2016). This dramatic shift in land ownership coincided with concerted state and national efforts to suppress wildland fires and terminate Indigenous cultures.

The University forest is a 1375-hectare research forest established within the FDL Reservation in 1909 near the lumber mill city of Cloquet. The University forest is 50 km southwest of Lake Superior (Gichi-Ojibwe-gamiing) and lies on a rolling sand plain that spans a subtle height of land between the Lake Superior and Mississippi River (Mishi-ziibi) watersheds. Fire-shaped pine barrens functioned as an overland travel corridor that connected the historical and contemporary FDL communities of Cloquet (Mookomaani-onigaming) and Sawyer (Gwaaba-iganing). A narrow stream called Otter Creek (Nigigo-ziibiwishe) is the most distinctive perennial water feature in the University forest.

Establishment of the University forest coincided with a campaign to entirely exclude fire from the property following widespread logging. The primary goal of the first forester-in-charge was to create a network of roads and fire breaks to prevent the loss of timber resources to fire. The work was effective. Interestingly, university records indicate no lightning-caused fires on the forest since 1910. Human-caused fires, however, were common, with "blueberry pickers" linked to several ignitions in the early 1900s (Schantz-Hansen 1960). By 1933, additional resources and workforce brought an end to reoccurring human-caused wildfires. Over the same period, university researchers documented the fire-influenced character of the forest that was typical of many pine forests in the region, with a ground cover of abundant wild blueberry plants (miinagaawanzh; *Vaccinium angustifolium*, *V. myrtilloides*) and other species typical of fire-maintained sites (Fig. 1; Schantz-Hansen 1923). Wood sections from fire-scarred red pine identified at least five fire years between 1820 and 1894 (Schantz-Hansen 1931).

An expanded tree-ring fire-scar record

Dendrochronological research in 2016–17 updated and expanded fire history for the University forest based on fire scars recorded by 64 red pine (bapakwanagemag; *Pinus resinosa*) stumps and snags. Twenty-seven fires were documented between 1730 and 1909, after which fires abruptly stopped (Fig. 2). The open forest conditions of the early 1900s had developed amidst frequent, low-severity fires, yet the current fire-free interval for much of the forest is over 115 years. Information shared by FDL community members since 2017 reinforced the likelihood that fire absence over the last century is better explained by the decline of intentional ignitions than fire suppression alone.

Cultural context from Indigenous oral history

Diverse sources document Great Lakes Anishinaabe relationships with many plants associated with fire-influenced sites. Wild blueberry (miinan) was a particularly important food and medicine in Anishinaabeg economies (Norrgard 2014), and "blueberry

Figure 1: Historical (left) and current (right) forest conditions in the Camp 8 stand (Fig. 2), one of the sites sampled for fire history. Euro-American fire suppression practices that prohibited Indigenous fire stewardship gradually shifted fire-maintained open woodlands and forests to fire-excluded states that would be unrecognizable to the inhabitants of these landscapes a century ago (Source: University of Minnesota Archives; Eli Sagor).

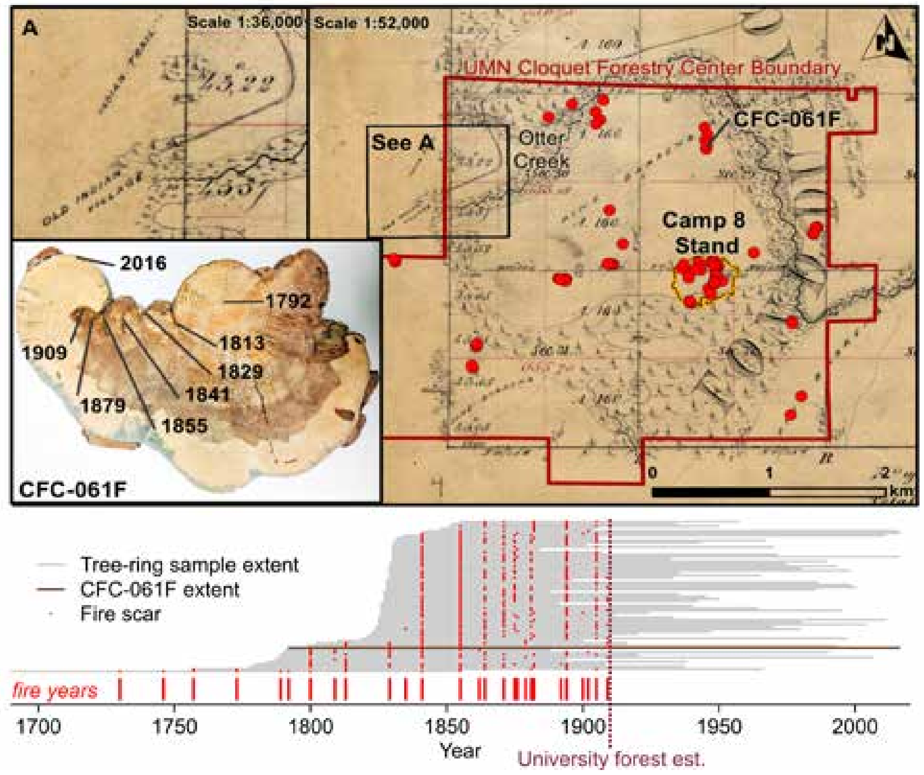

Figure 2: The 1868 General Land Office survey mapped pine barrens across the uplands of what is now the University forest. A seasonal Anishinaabe camp at the Otter Creek headwaters is shown in inset **(A)** (Source: Bureau of Land Management). Fire history sample locations are shown as red dots. One of the sampled fire-scarred trees, CFC-061F, is indicated on the map and the analyzed sample is shown at left. A fire history chart for the study area is shown below, with horizontal lines representing the record of individual trees and red ticks as detected fire years.

pickers" knew that the abundance of heavily-fruiting blueberry plants was most predictable in recently burned areas. Anishinaabe memories of berrying traditions are widely held (Peacock 1998), and fire-maintained berrying sites were visited each summer for a harvest that lasted up to six weeks. Anishinaabe knowledge-keepers often share that their ancestors tended blueberry sites with the regular application of fire to rejuvenate blueberry plants (Berkes and Davidson-Hunt 2006). With the great disruption of traditional land-use practices since colonization, there is fading knowledge of specific berrying sites where fire was regularly used. In cases where place-based information has been lost, recorded Indigenous oral history can supplement community memory.

In the case of the University forest, a group of Fond du Lac tribal elders interviewed in the late 1970s (Boundary Changes 1978–1979) recalled a thriving berry economy circa 1900 centered on what is now the University forest. One of the knowledge-keepers, Elizabeth Danielson, was born in 1888 and referred to vegetation conditions in her mother's time. The land around Otter Creek was "not heavily timbered then" but "brush like, regular blueberry country" (Danielson 1978). Prior to University acquisition, the Otter Creek headwaters was a destination for Anishinaabe families during the blueberry season, one of only two times each year when families from across the reservation would gather in one place (Danielson 1978). The abundance of berries was such that buyers would travel from Cloquet to Otter Creek daily to purchase berries by the bushel, paying 10 cents a quart (Whitebird 1978). Evidence of this traditional community use was recorded in the 1868 General Land Office survey as an "Indian trail" and "old Indian camp" just north of Otter Creek, opposite swaths of pine barrens observed to the south and east (Fig. 2).

With the exclusion of Anishinaabe land-tending practices following establishment of the University forest, blueberry production declined, an unintended consequence of Euro-American fire exclusion practices. Frank Whitebird stated directly the effects of white settlement and changed land-use on the University forest and the broader FDL Reservation: Blueberries were "…like cranberries you know. After white man gets them. No more cranberries." (Shabaiash 1979).

Fire restoration with blended knowledge as guide

Blending tree-ring fire history with Indigenous memory enhances our ability to interpret the fire record and vegetation change in the Upper Great Lakes Region. Fire-scarred trees serve as tangible reminders of fire's importance in shaping landscape biodiversity and ecological integrity. When cultural context is provided, fire-scarred trees and remnants become biocultural artifacts and discrete components of Indigenous cultural landscapes. When the tree-ring fire-scar record is understood as an eco-cultural phenomenon, it undermines the terra nullius, or "the land of no one", narrative that has shaped public discourse on North American wildlands for over a century (Vinyeta 2021).

A convergence of tree-ring fire history, contemporary Indigenous knowledge, and documented oral history on the Fond du Lac Reservation explains the mechanisms behind the frequent fire record at the University forest and highlights fire restoration as the continuation of a long relationship between people and land. The tree-ring fire record at the University forest matches patterns of fire history across large portions of the Upper Great Lakes Region where frequent fire was shut off with the widespread colonization of Indigenous lands circa 1900. A blended knowledge approach to fire history creates the potential to transform how tree-ring fire records are applied to contemporary, cross-cultural forest stewardship with fire restoration as both an ecological process and traditional cultural practice. This blended knowledge approach is guiding collaborative fire restoration at the University forest.

ACKNOWLEDGEMENTS

Miigwech to Gwiiwizens aka Ricky DeFoe for sharing his knowledge of Anishinaabemowin language for this piece.

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doi.org/10.22498/pages.30.1.38

Landscape conservation and the ancient technique of pastoral fire in the western Pyrenees

Michael R. Coughlan[1], T.L. Gragson[2] and D.S. Leigh[3]

Multi-proxy evidence suggests that pastoral fire use has spanned thousands of years in the western Pyrenees. Our place-based integration of traditional knowledge with paleoecological, historical, and archaeological sciences points to Basque pastoral burning techniques as effective tools for conserving the cultural landscapes of the Pyrenees.

Basque stock raisers (*éleveurs* in French) in the western Pyrenees use fire as a tool to manage hedgerows and to clean and renew meadows and pastures (Coughlan 2013, 2014). Scholars generally recognize that the practice of "pastoral fire" (*feu pastoral* in French) is ancient and that it historically played a significant role in land management in the Pyrenees (Métailié 2006). Yet, the practice of pastoral fire is heavily regulated by the French state and continues to be regarded with suspicion by many forest- and fire-management officials who consider it a haphazard and environmentally irresponsible practice (Coughlan 2013). Given these competing narratives, the appropriateness (perhaps necessity) of pastoral fire as a landscape conservation tool is seldom considered.

Our place-based investigation of pastoral fire integrates diverse types of knowledge (i.e. traditional knowledge in addition to historical, archaeological, and paleoecological archives) to understand when the practice first began and the long-term effects of burning on soils and vegetation patterns within an ethnically Basque province of Soule (*Xiberoa* in Souletin Basque) in the French western Pyrenees. Our results point to traditional pastoral fire use as a practical and effective tool for conserving ancient cultural landscapes comprised of forest-meadow mosaics and seasonal upland pastures.

Ethnography of pastoral fire use

Basque peoples have likely inhabited the western Pyrenees for at least the last several thousand years, culturally adapting to, and shaping, the environment there (Gragson et al. 2020). Generation after generation of Basque shepherds have successfully passed on the place-based traditional knowledge of how to burn landscapes in ways that help to ensure the long-term sustainability of ecosystem goods and services.

Following this long tradition, today's stock raisers set culturally prescribed fires in the mid-elevation mountains (300–800 m asl) with relative ease during mid to late winter months, and higher up the mountainside in the early spring. Bracken (*Pterdidium* spp.) and false broom (*Brachypodium sylvaticum*) growing in the mid-elevation forest-meadow matrix are the first to be burned. These fires remove the unpalatable cured grasses from the previous growing season, but also burn seedlings and new sprouts from tree roots, which prevents the encroachment of trees into pastures and meadows. New grass shoots soon appear, resulting in nutrient-rich forage for the transhumant livestock herds as they are shepherded toward higher elevation summer pastures (Fig. 1).

This burning usually takes place in February and March, when the weather patterns have shifted from a cool and wet Atlantic pattern, to a sunny and warm Mediterranean pattern, driven by dry Foehn winds. Fuels are cured and ready to burn after about three days of sunny, warm weather, and fires spread rapidly until petering out at the edge of the forest where they are extinguished by the more humid, less flammable fuels under the beech (*Fagus sylvatica*) forest canopy. On more sheltered slopes, clumps of heather (*Calluna vulgaris*) and gorse (*Ulex europaeus*) are generally ignited individually. These burn rapidly, creating copious amounts of smoke, but due to their patchy growth, they require multiple ignition points. Common juniper (*Juniperus communis*) is treated similarly at higher elevations. Burning above 800 m asl generally begins in late March and runs into May, although smaller fires, sometimes targeting individual shrubs, are set throughout the summer months.

Paleoecological evidence for woodland-to-pasture conversion

Multiproxy paleoecological evidence (i.e. charcoal, soil magnetic susceptibility, acrolein and polycyclic aromatic hydrocarbons, chemical compounds that are indicative of fire and strongly bound to soil particles) derived from stratigraphically sampled slopewash deposits (zero-order, small hollow colluvium) show a distinct increase in fire activity around 5000–6000 yr before present (BP), based on radiocarbon chronologies (Fig. 2; Leigh et al. 2015, 2016; Gragson et al. 2020; Coughlan et al. in press). These paleoenvironmental archives occur in continuous sedimentation records from about 18,000 yr BP to the present and

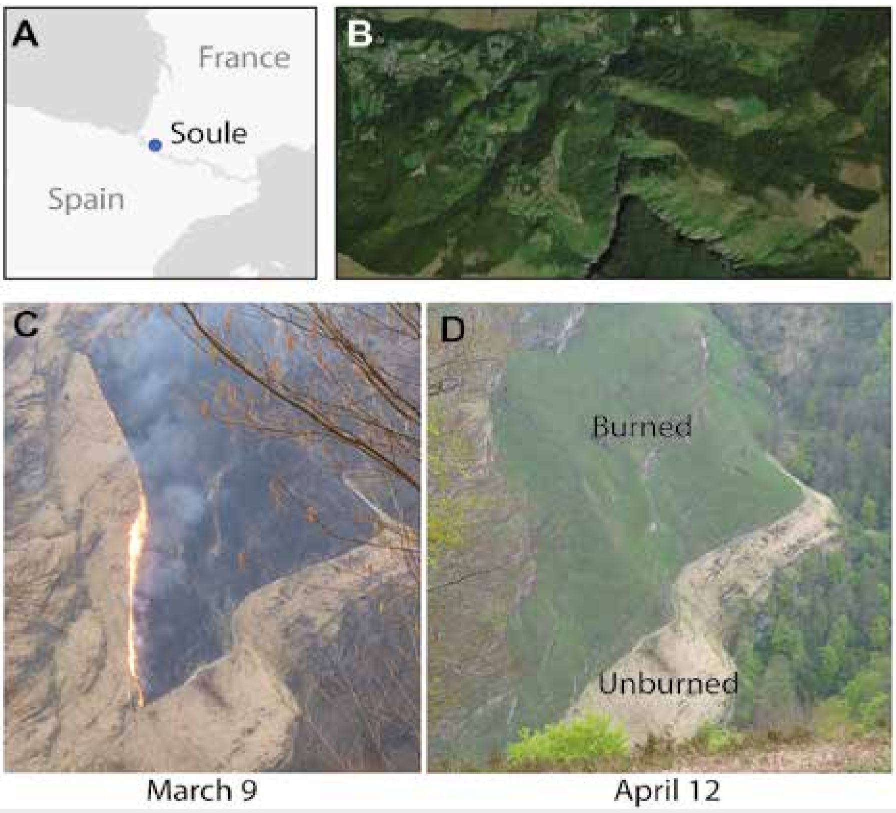

Figure 1: (A) Location of Soule (Xiberoa); **(B)** Basque cultural landscape mosaic; **(C)** Photo of pastoral fire lit on 9 March 2011 above a footpath serving as a firebreak; **(D)** Photo of the same area about a month later on 12 April. The burned grasses have re-sprouted with renewed growth, whereas the unburned area remains covered in last year's less palatable cured grasses (photo credits: Michael Coughlan).

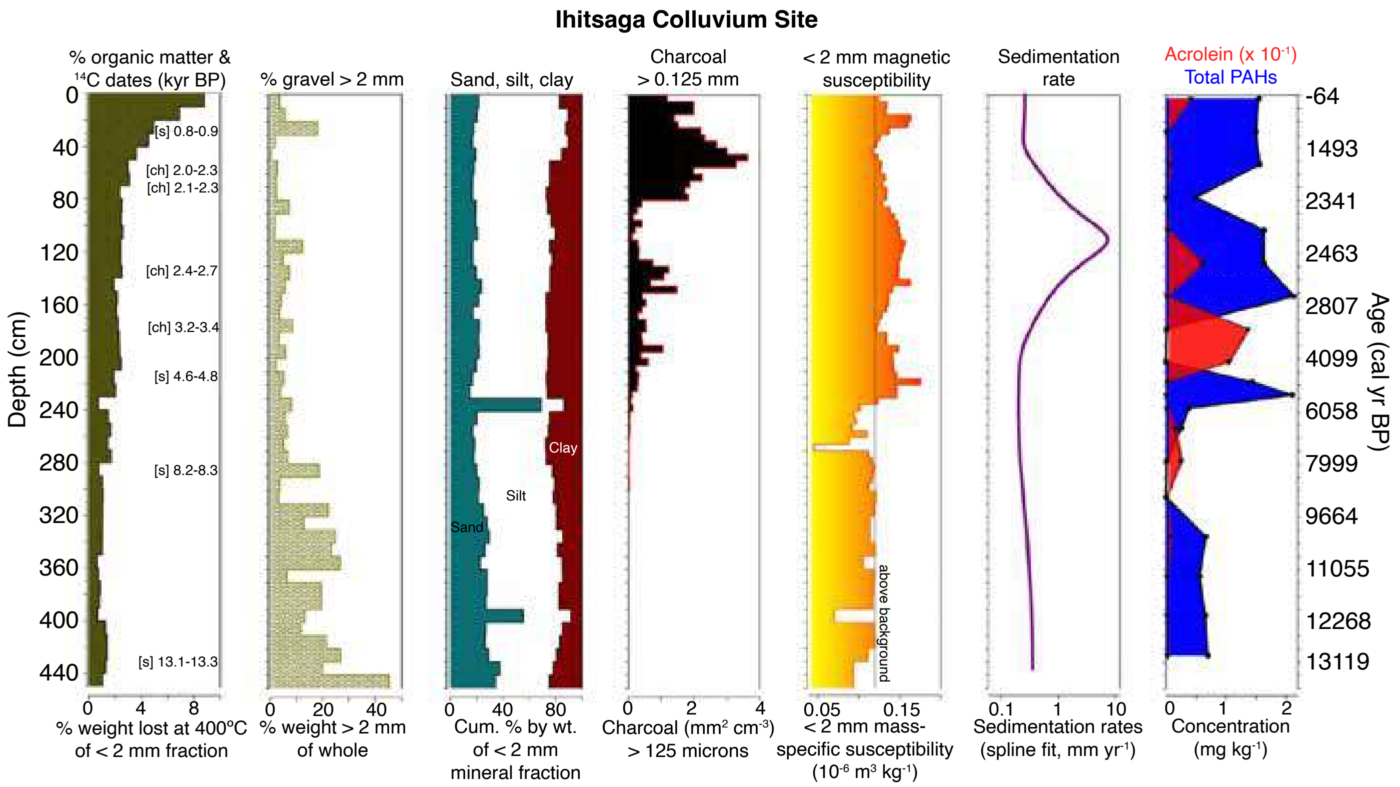

Figure 2: Multiproxy evidence for fire from the "Ihitsaga" sample site, a zero-order hollow along the Pyrenean divide. Radiocarbon dating samples are indicated by [s] for soil matrix and [ch] for charcoal with ages in thousands of years before present (kyr BP).

suggest that late Neolithic people pioneered intentional use of fire in a region where natural fires were rare (Jalut et al. 2000). Non-synchronous peaks in proxies from different sediment sample sites indicate a highly localized, as opposed to regional, pattern of fire use, especially during the Neolithic through to the Bronze Age. Following the Bronze Age, charcoal concentrations steadily increased or remained high, indicating widespread use of fire. Pronounced sedimentation rates spike in conjunction with some of the Iron Age through Middle Age peaks in charcoal, suggesting excessive levels of soil erosion, but sedimentation rates generally settled down by Modern times. Thick, organic-rich horizons of modern soils indicate that the fire-based land management practices contribute to sustainability of soils.

Historical and archaeological evidence for the persistence of pastoral economies

An archaeological survey of approximately 4710 hectares of upland pastures (elevations greater than 800 m asl) located nearly 200 archaeological features (stone and earthen foundations, enclosures, and mounds) thought to be associated with seasonal herding activities (Le Couédic et al. 2014). Based on 24 radiocarbon dates of charcoal from seven widespread archaeological features, land-use intensity in the upland pastures peaked only in the last 1000 years (Gragson et al. 2020; Coughlan et al. in press). This archaeological evidence for land-use intensification coincides with historical and archaeological evidence for year-round settlement of nearby farming households located between 300 and 600 m asl. Historical records show that farming communities accessing the upland pastures in Soule have existed since at least the 11th century CE (Gragson et al. 2020). Diverse historical documents suggest that many of the household farm estates at the foot of these pastures were established at least 500–600 years ago, but some of these were abandoned in the latter half of the 20th century (Gragson et al. 2015; Coughlan and Gragson 2016).

An archaeological survey of approximately 18 household farm estates and surrounding communal areas suggested that settlement density, in terms of domestic and agricultural structures, reached its maximum around the late 18th to early 19th century (Coughlan and Gragson 2016). This timing coincides with parcel-level land-use mapping recorded in the 1830 Napoleonic cadaster, thus providing a record of the landscape at its most intensive period of use. Records and observations from recent decades show that pastoral fires have been confined to areas that were registered as pasture land-use in the 1830 cadaster (Coughlan 2013). Comparison of historical aerial photos (1940s-2003) and digitally mapped cadastral records from the 1830s suggest that forest–pasture edges have remained relatively stable over the last 200 years. Further, tree-ring archives show that trees along the forest-pasture boundaries predate the 1830 mapping efforts (Gragson et al. 2020). In other words, despite persistent and frequent use of fire, pastures have not expanded beyond their 1830 boundaries.

Implications for landscape conservation

The integration and synthesis of these diverse forms of evidence suggest that pastoral fire is a stable management practice that has helped to maintain a cultural landscape mosaic of pastures and forests (Coughlan 2014). Contemporary Basque stock raisers face a number of social and economic challenges, and many are abandoning agriculture altogether. A small number of remaining stock raisers continue to employ traditional burning techniques, but find it difficult to meet their management goals while complying with protocols spelled out in official regulations. Land managers and policymakers in Europe and elsewhere can learn from traditional pastoral fire and should make efforts to facilitate the continuation of this vital ancient management practice.

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doi.org/10.22498/pages.30.1.40

Socio-ecological vulnerability and adaptation of southwestern Malagasy to changing environment and climate

Estelle Razanatsoa and Lindsey Gillson

In the face of a changing environment linked to increased drought and depletion of natural resources, paleoecological data of the last 2000 years show how communities in southwestern Madagascar adopted both incremental and transformational adaptations that allowed them to cope with environmental variability.

SW Madagascar: a case study illustrating a global challenge

Dealing with the consequences of climate change on Earth requires conserving the world's biodiversity, while managing ecosystem services sustainably. Sustainability requires meeting the needs of current and future generations, and keeping open their options to adapt (United Nations 2015). Understanding landscape history can help to determine what is sustainable in a changing environment, while understanding adaptations of past societies may provide stakeholders with a more solid basis for dealing with future changes (e.g. Razanatsoa et al. 2021).

This approach is particularly important in climate hotspots as these areas will experience higher magnitudes and rates of change in the near future (United Nations 2015). Vulnerability to future climate change is exacerbated in areas such as southwest Madagascar, where natural resources are already being depleted (Razanatsoa et al. 2021). Southwest Madagascar is known for its arid climate, receiving less than 500 mm per year of rainfall on average. The region is currently experiencing recurrent droughts that are predicted to become more extreme in the future (Waeber et al. 2015; Masson-Delmotte 2021).

Climate reconstructions show variable climate conditions in Madagascar, with evidence of drier phases over the last 2000 years (Vallet-Coulomb et al. 2006; Virah-Sawmy et al. 2016). Multiple lines of evidence have pointed out changes in ecosystems in the region responding to this climate variability (e.g. Godfrey et al. 2021; Razanatsoa et al. 2022; Virah-Sawmy et al. 2016) but also to land-use change as a response to environmental change. Increase in grass abundance was recorded around 1 kyr BP and the near present time, both linked to changes in land use particularly with the use of fire (Razanatsoa et al. 2021). In these landscapes, humans have adapted to changing climate both "incrementally", i.e. through an extension of activities to their existing livelihood, or adopting a more "transformational" approach, i.e. with shift from one form of activities to another (Kates et al. 2012).

Contrasting livelihood strategies

Southwest Madagascar is presently occupied by agropastoralists and forager communities. Agropastoralism dominates around Longiza, while foraging is still prevalent near Tsizavatsy (Fig. 1). Over the last 2000 years, these communities have adapted their livelihood in response to environmental change and economic growth (Razanatsoa et al. 2022).

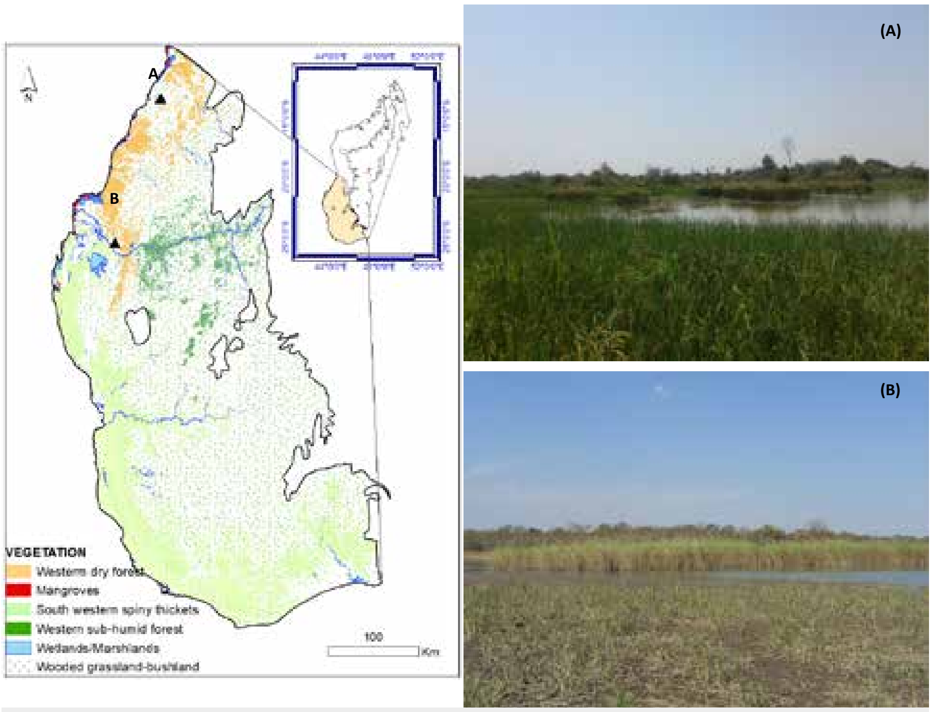

Figure 1: Southwest Madagascar's vegetation with the location and pictures of the sites investigated here: **(A)** Lake Longiza and **(B)** Lake Tsizavatsy.

The communities living around Lake Longiza currently practice agropastoralism as their main livelihood, but have shifted their subsistence strategies and livelihoods over time. Early occupants of the southwest region were probably foragers (Anderson et al. 2018). Increasing charcoal influx and coprophilous spore concentration (Fig. 2) suggest that fire has been used to support agricultural practices and pastoralism activities in the area since 600 CE (Fig. 1; Anderson et al. 2018). The first charcoal peaks at Lake Longiza are recorded around 1300 CE (microscopic charcoal) and 1500 CE (macroscopic charcoal), suggesting that pastoralism started around that time. Domestic cattle were introduced to the island of Madagascar around 700 CE, and expanded to the southwest by 1300 CE. Dung fungal spores reflecting the presence of herbivores likely indicate a shift in human practices from foraging to agropastoralism (Razanatsoa et al. 2022).

In contrast to the transformational shift in livelihoods near Lake Longiza, people near Lake Tsizavatsy have demonstrated a form of incremental adaptation in response to drying, and the associated changes in resources (Razanatsoa et al. 2021). Following a marked increase in fire activity at the beginning of the 20th century (Fig. 2), fire activity remained constant during the following decades, maintained by the current practices of swidden agriculture between December and March (Razanatsoa et al. 2021; Fig. 2). In response to the drying in their region, the Mikea communities living in southwest Madagascar reinforced their traditional practices of foraging (mainly used during the 13th century), and incorporated seasonal agriculture as a new coping strategy in the 20th century (Razanatsoa et al. 2021).

Local adaptations to drying climate

Paleorecords from the region indicate massive environmental changes (e.g. Razanatsoa et al. 2022). Around Lake Longiza, the communities abandoned their initial foraging practices to become agropastoralists (Razanatsoa et al. 2022). Such a transformation was likely possible because the region is currently known to have higher sources of water through river systems, more fertile soils (compared to the south), and is supported by international trade.

Such a shift was probably not possible around Lake Tsizavatsy because of the less fertile soils with unconsolidated sand (Seddon et al. 2000), and the more arid conditions. As a result, a complete abandonment of foraging is less likely at Lake Tsizavatsy, as water availability is too unpredictable to sustain permanent agropastoralism. Thus, agropastoralism provides an additional livelihood when conditions permit, but foraging remains important, especially in years that are too dry to support crop cultivation. Although experiencing a decreasing trend of rainfall and recurrent drought, the adaptation of these two communities depended entirely on local environmental conditions.

The aforementioned factors including the change in land use and climate variability have contributed to changes in the vegetation in southwest Madagascar. Increase in Poaceae (ca. 51% to 65%) suggests an opening of ecosystems around 1900 CE linked to agropastoralism around Lake Longiza (Razanatsoa et al. 2022), likely at the expense of a more diverse and heterogeneous landscape. With changing climate conditions, evidence of increasing dry-adapted plants is recorded around 1000 CE and 1700 CE (Razanatsoa et al. 2022). In particular, these led to a decrease in natural resources for the early forager communities and the need for new subsistence strategies at the expense of the local biodiversity.

Outlook

More challenges for food production, and, thus, food security, are expected for the African continent under a 1.5°C global temperature increase accompanied with increased drought in arid and semi-arid regions (Serdeczny et al. 2017; Masson-Delmotte 2021). Paleoecological data show that the decline and shift in vegetation associated with a reduction in ecosystem services such as fuel wood, sources of food, and medicine for these resource-dependent communities will lead to changes in human livelihood (Razanatsoa et al. 2022). Previous shifts in subsistence strategies have been attributed to factors including (but not limited to) the arrival and expansion of pastoralism and international trade.

While agropastoralism continues to expand with the growing population in Madagascar, the capacity of landscapes to sustain this is finite. In addition, a decrease in rice and maize production is projected in tropical regions under a +2°C scenario, making such practices less sustainable (Challinor et al. 2016). With these projections, current livelihoods will become more challenging, requiring more transformational and incremental adaptation. However, adaptation strategies should consider biotic and abiotic components of ecosystems in order to maintain the ecological infrastructure that will ultimately sustain the survival of its people. These last forager communities are likely to be forced into a larger shift in their livelihoods as they become more vulnerable (Razanatsoa et al. 2021), highlighting the need for more diversified livelihoods. This could be achieved through the participation of local and national stakeholders in formulating coherent adaptation strategies to enhance the resilience of forest-dependent communities to a changing climate (Saalu et al. 2020) but also the establishment of self-organized local institutions within local and Indigenous communities (Berman et al. 2020).

These case studies reflect a broader context on how social and ecological dimensions of biodiversity conservation and climate change adaptation can be in conflict, and should be tackled together. Paleodata provides insight into what happened in the past and how various communities adapted their livelihood to past environmental changes, and provides a basis for exploring future scenarios. It is important to note that the challenges people and ecosystems are facing today are unprecedented. Such challenges can only be tackled through collaboration and integration of various forms of knowledge into scenario planning and policy, if both the quality of life and level of biodiversity are to be maintained in a changing world.

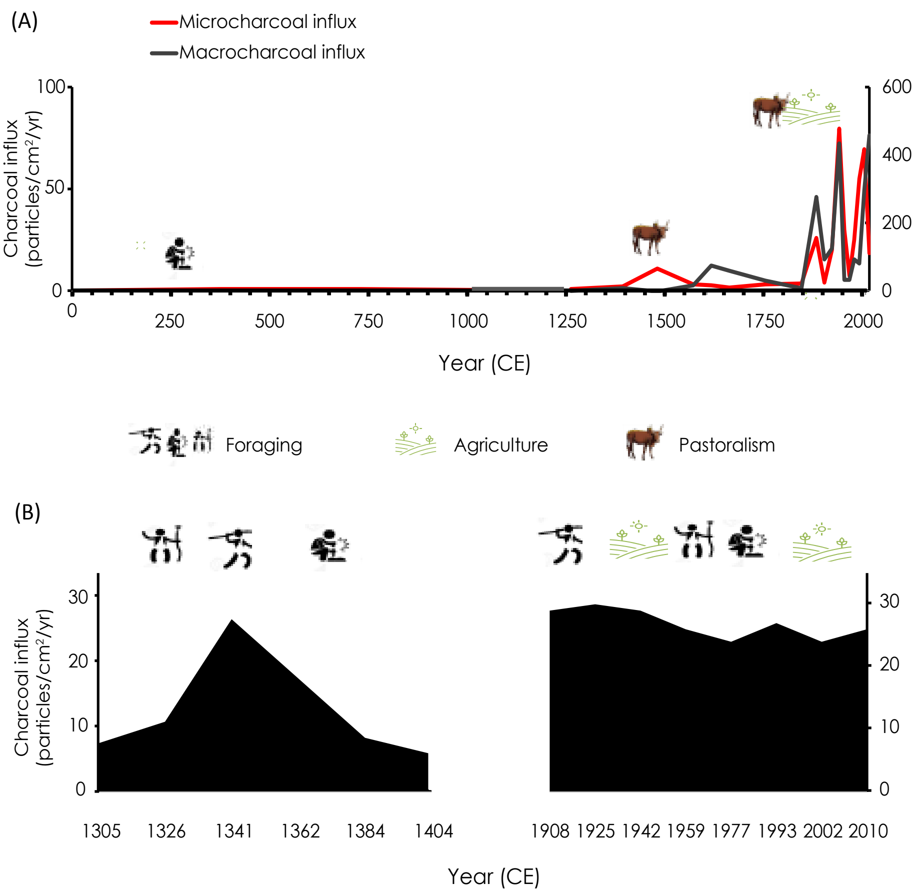

Figure 2: Fire variability inferred from charcoal records and associated livelihood practices. **(A)** Lake Longiza covering the last 2000 years (adapted from Razanatsoa et al. 2022); **(B)** Lake Tsizavatsy covering the 14th and 20th centuries (Razanatsoa et al. 2021).

ACKNOWLEDGEMENTS

We acknowledge support from a faculty PhD fellowship (University of Cape Town), the Applied Centre for Climate and Earth Systems Science (ACCESS NRF UID 98018), the University Research Committee (URC) accredited by the University of Cape Town, the NRF/SASSCAL (Southern African Science Service Centre grant number 118589), the NRF/African Origins Platform (grant number 117666), and the NRF Competitive Programme for Rated Researchers (Grant Number 118538).

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doi.org/10.22498/pages.30.1.42

Combining paleoecological and archaeological records to inform fire management and ecosystem conservation in Killarney National Park, Ireland

Donna Hawthorne[1], D. Colombaroli[2] and F.J.G. Mitchell[3]

Combined paleoecological and archaeological records allow for a detailed examination of past fire–human–vegetation interactions. Focusing on a national park at risk from increasing fire threats, we explore the potential of integrated approaches to inform future fire management and conservation policy.

Fire is increasing in many natural and cultural landscapes due to ongoing climate and land-use changes (Bowman et al. 2020), with potentially long-lasting consequences on ecosystem structure and composition (Kelly et al. 2020). In Ireland, the occurrence of recent wildfires in national parks represents a key challenge for park managers. For example, on one of the hottest days in Ireland in 2021, a fire blazed through ~1400 hectares of land in Killarney National Park (KNP), severely degrading existing habitats and wildlife. The fire burned for four days and was the largest fire that had occurred within at least the last two decades.

Fires have been increasing in frequency and severity in the region in recent years; however, the scale and impact of the 2021 fire was much larger than expected. In order to mitigate the effects of such catastrophic events, there is a growing need for park managers to understand how ecosystems responded to past fire variability. In Ireland, such a long-term perspective can be provided by multi-site comparisons of archaeological and paleoecological records, offering new insights into the anthropogenic and climatic drivers of past fire regimes (Whitlock et al. 2017). Such long-term perspectives can be used to inform the development of fire management strategies appropriate for varying land-use, climate, or vegetation scenarios (e.g. Willis and Birks 2006; Colombaroli et al. 2017; Brown et al. 2018; Gillson et al. 2019).

Integrated, long-term perspectives are particularly needed in regions where forest management practices such as fire suppression and fire exclusion over the past century have led to largely fire-free landscapes. The primary goal of fire suppression/exclusion is often to protect natural heritage, e.g. semi-natural native woodlands, and is a common practice in Irish national parks. This has likely been the case for KNP since the park's creation in 1932 (and formally since at least 2005, with the creation of a fire-fighting action plan for early wildfire detection and control). Woodlands and grasslands in the park are particularly at risk from severe wildfires, causing woodland margins to recede. Here, we discuss how the combination of archaeological and paleoecological evidence can provide key information about the long-term effects of fires on landscapes, and how such integrated knowledge can better inform ecosystem management in the park.

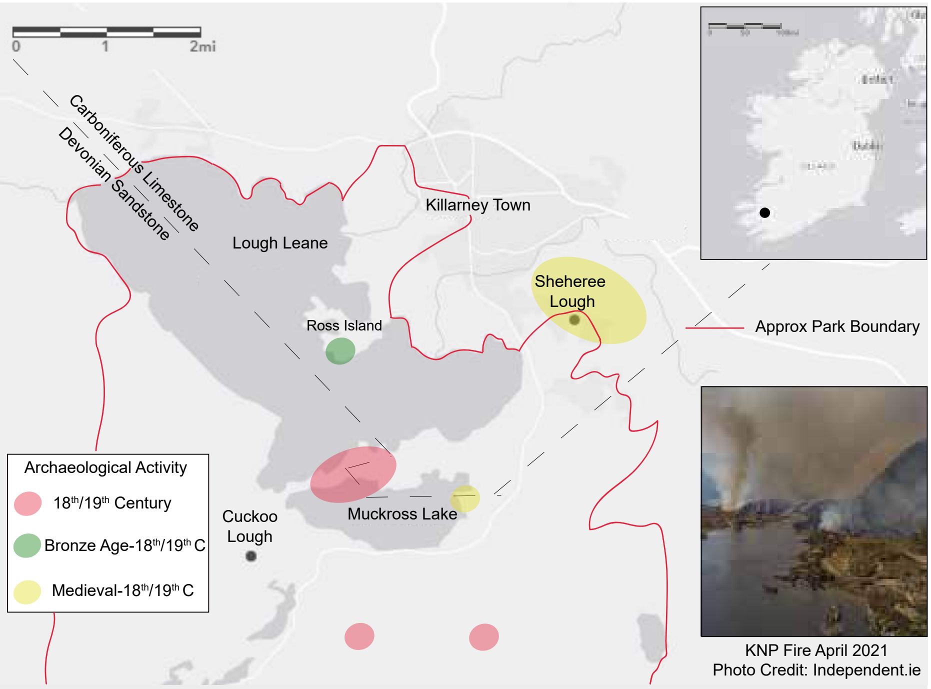

Figure 1: Map of Killarney National Park (KNP), including the location of study sites, underlying geology and archaeological activity. Inset top: location of KNP within Ireland. Inset below: fire in KNP, April 2021.

Long-term fire-vegetation-climate interactions

Pollen and charcoal records from two study sites within KNP (Cuckoo Lough: uplands, and Sheheree Lough: lowlands; Fig. 1) provide insights into past fire regimes at the transition from a semi-natural forest to the establishment of modern anthropogenic landscapes. The two sites overlie different bedrocks and elevation, thus highlighting differences in fire trajectories and vegetation development at a more local scale. Paleoecological data show that fire has been part of the Killarney landscape since at least the Late Glacial (ca. 20,000 yr cal BP), which predates all evidence for human occupation (Hawthorne and Mitchell 2018). Peaks in fire activity at ca. 8000–5000 yr cal BP in the lowlands and ca. 7000–4000 yr cal BP in the uplands, coincided with climate amelioration and increased seasonality during the early Holocene (Ghilardi and O'Connell 2013; Mitchell and Cooney 2004). A later peak in fire activity occurred in the uplands ca. 2500 yr cal BP (Fig. 2).

According to the archaeological and paleoclimatic evidence, these maximum fire conditions were largely driven by climate conditions conducive for fire, and enhanced by moderate anthropogenic activities. Climate at the time made the environment more receptive to both natural and anthropogenic fires. These fire periods are associated with an overall decline in fire-sensitive tree taxa (e.g. *Ulmus*), increases in fire-enhanced species (e.g. *Alnus*) and the expansion of open, more flammable shrubs and grasses (e.g. *Corylus* and Poaceae). Importantly, microsite conditions (altitude and bedrock) influenced how the different vegetation responded in the long-term, by promoting individual taxa locally (e.g. increases in *Corylus*, *Alnus*, *Betula*, and *Quercus* during the Late Neolithic-Bronze Age (5000–2500 yr cal BP).

The increasing role of humans driving fire and vegetation changes in the KNP

Over the last few millennia, fire controls shifted from climatic to predominantly anthropogenic. Fire disturbances increased, particularly since the Bronze Age, when a combination of human activities in different areas of the park had a long-lasting and pervasive effect on vegetation structure and composition (Hawthorne et al. 2021).

Combined paleoecological and archaeological data show significant differences in the timing and intensity of human activity at both sites. Conditions in the uplands were less suitable for agriculture due to their lower fertility, and human activity was rather low until the 18th–19th centuries (Cuckoo Lough; Fig. 2). In contrast, in the lowlands (Sheheree Lough; Fig. 2), periods of increased fire activity (~3800 yr cal BP and ~1300 yr cal BP) roughly correspond to mining activity (e.g. between 3900–3400 and 1300–1000 yr cal BP; see O'Brien 2004), despite the wet and cool climatic conditions at that time (~4250 and 3750 yr cal BP; Swindles et al. 2013). From ~3500 yr cal BP evidence for the expansion of agriculture, suggests that these practices supported the Bronze Age mining activities on nearby Ross Island, which peaked ~3300 yr cal BP and continued until the 18th–19th centuries (O'Brien 2004). Forest decline continued in the last ~1000 years, synchronous with archaeological sites dated to the Early Medieval period. Taken together, the matching paleoecological and archaeological evidence shows the transition from ecosystems largely shaped by anthropogenic fires to the final establishment of more open landscapes, presently under more fuel-limited conditions.

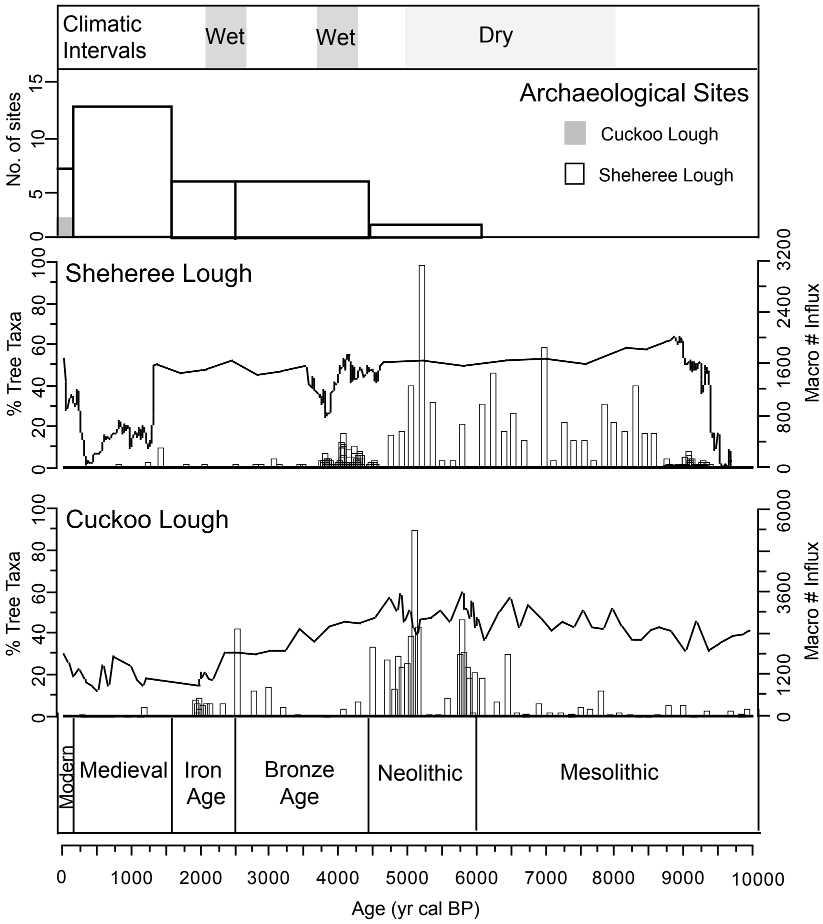

Figure 2: Summary of paleoecological and archaeological evidence from Cuckoo and Sheheree Lough, by archaeological period. Macroscopic charcoal influx (particles/cm²/yr; bars) is presented with total tree taxa (%; line). Number of archaeological sites are also presented with wet and dry climatic periods denoted from the literature.

Implications for fire management and ecosystem conservation in the park

Current fire management plans within KNP are limited to fire detection and control/suppression, with the priority of preserving the park's archaeological and natural heritage. Such management strategies are presently challenged by the occurrence of severe fire events during exceptionally dry years. The frequency and severity of fires in Ireland has been increasing in the past decade, and there is a clear and growing need for management strategies to meet these new challenges.

Paleoecological and archaeological data can assist in identifying best approaches that can guide future conservation and landscape management strategies (e.g. Gillson 2019; Whitlock et al. 2017). In the case of KNP, records show that fires were part of the park's long-term history, similar to other temperate regions (Whitlock et al. 2015, 2017). In the past, maximum fire conditions occurred when climate conditions were conducive for fires, and fire activity was intensified by moderate human impact (e.g. between the Late Neolithic-Bronze Age; Fig. 2). In the long term, such fire activity was important for maintaining species that are more fire-adapted locally (e.g. *Corylus*, *Alnus*, *Betula*). The establishment of open habitats only occurred when agricultural practices intensified, leading to marked reductions in forest biomass.

Overall, the KNP case study shows how both climatic and anthropogenic factors created a complex mosaic of vegetation communities, which supported varying fire regimes over time. These historical legacies on present landscapes are key for understanding the conservation of landscapes under current and future climates (Whitlock et al. 2017). Today, the hyper-oceanic climate of the region renders the lowland native broadleaved woodland less fire-prone; however, this may change rapidly under future warmer temperatures (de Rigo et al. 2017). In contrast, in upland areas the open land between woodland patches is dominated by the heather *Calluna vulgaris* and the grass *Molinia caerulea*, fire-prone vegetation types, which in turn could impact the edges of the woodlands. Open *Calluna vulgaris* and *Molinia caerulea* communities are maintained by grazing from deer populations; hence, a reduction in deer numbers would permit woodland expansion and, thus, reduced scope for fires under present climatic conditions. Instead, the pasture land in the lowlands is managed more intensively and tends not to support fire. A more robust, evidence-based plan for the conservation and management of the park can be achieved by conservation policies that better reflect conditions at the landscape scale, through the integration of all the available evidence, including modern, paleoecological, and archaeological.

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doi.org/10.22498/pages.30.1.44

Paleoscience–policy "commons": Connecting the past to a sustainable future in a human-dominated tropical biodiversity hotspot

Charuta Kulkarni[1] and Dhanya Bhaskar[2]

Building science–policy interfaces is essential for envisioning pragmatic environmental solutions. Drawing from the Western Ghats of India, we identify mutual areas of interest, or "commons", where specific environmental management issues can benefit from a long-term perspective, encouraging paleoscience–policy connections.

Achieving food security while maintaining biodiversity is a key challenge for tropical regions. Sustainable management of these regions is further threatened by global environmental changes that have serious impacts on livelihoods of billions (Gadgil and Guha 1993). Given the long histories of human occupation and the influence of past climates and land-use practices in shaping tropical landscapes, it is essential to incorporate both ecological and cultural legacies in their planning and management (Swanson et al. 2021). Conservation and restoration plans often fail to acknowledge the significance of such legacies (Gillson and Marchant 2014), resulting in conflicts between restoration targets and people's needs (Colombaroli et al. 2021). For example, management policies that are regulatory and/or restrictive (e.g. fire prevention, monoculture afforestation schemes) often contrast with traditional practices that support local livelihoods and undermine the crucial role of past ecological processes (Gadgil and Guha 1993).

With the term "commons", we refer to specific policy conservation/management issues that can benefit from a long-term perspective. Bringing examples from tropical paleoecology and environmental policy, we show how the identification of such mutual areas of interest is pertinent in establishing and expanding paleoscience–policy interfaces. We argue that identification of paleoscience-policy commons is a requisite for effective tropical landscape management where policy-relevant paleo-studies, as well as dialogs between scientific and policy circles, are rare, if not absent.

Tropical agroforestry systems: opportunities for integrating paleosciences into policy

Agroforestry, the practice of planting crops under or alongside trees, is one of the most widely used land management techniques worldwide (Fig. 1). While supporting the local livelihoods through encouraging intentional management of trees for productive agriculture, agroforestry is also recognized as a promising nature-based solution for the improvement of ecosystem functions, biodiversity conservation, and climate change adaptation (The 4th World Congress on Agroforestry, 2019). Tropical agroforestry landscapes are typical social–ecological systems that have existed for centuries or even millennia – especially those located in the biodiversity hotspots exemplify traditional practices and lessons for the future (e.g. Maezumi et al. 2018; Kulkarni et al. 2021). The Western Ghats, a 1600-km mountain range running parallel to the west coast of India, is one such biodiversity hotspot where tropical rainforests support the highest human population density. In the Western Ghats, high-resolution paleoecological data shed light on the transformation of local agroforestry systems since 4000 cal BP (Fig. 2), revealing their diverse ecological and social dimensions including ancient farming practices, their relationship with monsoonal variability, and fire as a land management strategy (e.g. Bhagwat et al. 2012; Nogué et al. 2018; Kulkarni et al. 2021). The perspectives drawn from these long-term interactions between tropical ecosystems and people offer vital clues for understanding the long-lasting benefits of agroforestry practices and their sustainable management, both of which are envisioned under India's National Agroforestry Policy for synergizing biodiversity conservation and livelihood benefits (Government of India 2014). Below, we present two commons where studies of past ecologies in the Western Ghats with a focus on local policy issues could aid in visualizing appropriate and inclusive management choices:

Figure 1: A typical tropical agroforestry landscape integrating native trees and crops (photo credit: Dhanya Bhaskar).

(1) Conservation and restoration in human-dominated tropical landscapes

India's National Agroforestry Policy focuses on ecosystem protection and resilient farming as important strategies to minimize climate risks (Government of India 2014). Land degradation in the past affected more than 30% of the country's geographical area, thus, in response, the Indian government has committed to restoring 26 Mha of degraded land by 2030 under the United Nations Convention on Combating Desertification (Press Information Bureau 2019). In this context, paleoecological studies show where conservation efforts should be focused and how these can be cognizant of local practices.

For example, pollen-based reconstructions of biodiversity in the Western Ghats highlight a high positive correlation between the canopy cover and plant diversity (Fig. 2), emphasizing the importance of maintaining tree canopies for nurturing highly diverse landscapes (Kulkarni et al. 2021). Paleodata in the Western Ghats also reveal the resilience of native evergreen trees towards

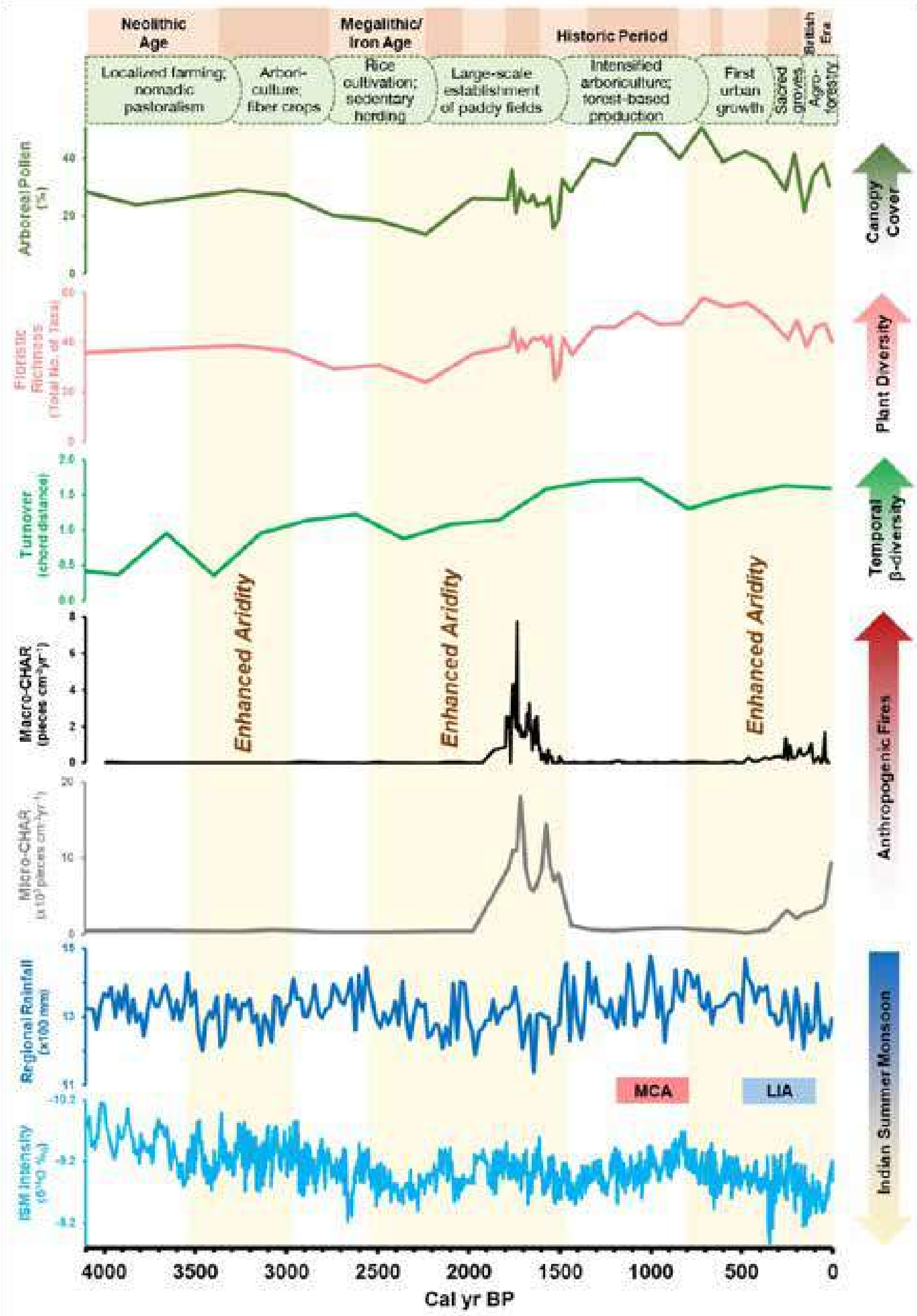

Figure 2: Transformation of the Western Ghats agroforestry landscape over the past 4000 years, showing changes in canopy cover, plant diversity, and fire in relation to the Indian Summer Monsoon variability (Modified from Kulkarni et al. 2021). Paleodata exhibit a high positive correlation between the canopy cover and plant diversity in the Western Ghats and sustained burning episodes during the periods of enhanced aridity, i.e. significant decline in the monsoon.

varying degrees of land-use change over several millennia. A few native species such as *Dipterocarpus*, *Hopea*, and *Palaquium* are already part of historic baselines and are incorporated in the current planning and restoration of the Western Ghats (Muthuramkumar et al. 2006). To this end, paleoscience imparts empirical support to the existing conservation strategies and recommends that maintaining patches of native trees on agroforestry landscapes should be a key priority for conservation and restoration efforts. This recommendation also speaks to the need for conservation beyond protected areas in human-dominated tropical landscapes, and the short-sighted rationale behind promoting exotic, fast-growing agroforestry species (e.g. *Eucalyptus*, *Casuarina*), often under government supported forestry programmes (Garcia et al. 2010).

(2) Fire in agroforested landscapes

Blanket bans on Indigenous fire practices since the colonial times has had serious repercussions on forest succession and forest-dependent livelihoods in many tropical regions (Gadgil and Guha 1993). Studies on fire management from different geographies, including those on traditional fire practices of *Soligas* in the Western Ghats (Sundaram et al. 2012) and of Pemón communities in Venezuela (Bilbao et al. 2010) unveil how outright banning of Indigenous fire practices leads to high-intensity catastrophic fires and the increased susceptibility of tropical forests towards fires.

In the Western Ghats, Kulkarni et al. (2021) show that sustained burning during dry periods (ca. 2000–1600 and 400–0 yr BP) resulted in increased canopy openings, subsequently reducing plant diversity (Fig. 2). Combined with local knowledge, they highlight how the re-introduction, or maintenance, of traditional low-intensity burns can help prevent fire-spread from peripheral agricultural lands into forest reserves, which are often in close vicinity in human-dominated tropical landscapes. This also implies that the slash-and-burn practices of tropical regions that are often portrayed as destructive, are in fact important in maintaining landscape mosaics and heterogeneity, preventing high-intensity fires and enhancing social-ecological resilience (Thekaekara et al. 2017).

Outlook

Expanding the list of paleoscience–policy commons and complementing them with historical and indigenous knowledge, can better uncover the complex drivers of tropical ecosystem transformations and the processes that maintain both natural and cultural values in landscapes. Such paleoscience–policy connections have the potential to incorporate long-term perspectives in environmental planning and can promote inclusive approaches within policymaking. This can also foster cross-sectoral and interdisciplinary collaborations at the science–policy interfaces (Swanson et al. 2021), enabling us to tackle future conservation challenges and secure livelihoods in the tropics.

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doi.org/10.22498/pages.30.1.46

Future fire predictions in light of millennial fire regime variability in Corsica, France

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Corsican biodiversity is threatened by both climate and disturbance-regime changes. Here, we simulate the future impacts of fires and discuss how integrated paleomodeling approaches can help assess future trends, in the context of the millennial-scale fire variability.

Over the past few decades, a surge in the number of large, uncontrolled wildfires has occurred worldwide, irrespective of national fire-fighting capacities or management policies. Global warming predicted by climate models for the next decades could further amplify this trend and threaten most ecosystems worldwide (e.g. Varela et al. 2019). In the Mediterranean basin, Corsica is a fire "hotspot" due to dry summers and traditional fire use (e.g. slash-and-burn practices). In the last five decades (1973–2019), 2369 large fires (> 10 ha) were recorded (promethee.com). This number could significantly increase in the future due to a combination of climatic changes and increases in human-caused ignition (Curt et al. 2016), with consequences on biodiversity, people, and infrastructure.

Corsican fire history

Fires have been frequent in Corsica for at least the last 11,500 years, with two main increases evidenced in paleoecological records (Fig. 1; Lestienne et al. 2020b).

The first increase between 11,500 and 7000 yr cal BP corresponded to the development of *Pinus* sp. forests during the Early Holocene, followed by shrubby ecosystems dominated by *Erica* sp. This ecosystem development increased the amount of fuel available near the ground and the connectivity between the ground and the tree tops, promoting crown fires (e.g. Curt et al. 2013). Independent proxy-based studies at the regional scale indicate that this period experienced hot and dry summer climates (e.g. Vannière et al. 2011), i.e. optimal conditions for wildfires to ignite and spread.

To model fire climate conditions, we used climate-model simulations and adapted two indices derived from the Fire Weather Index estimating the fire hazard (Van Wagner 1987): the Monthly Drought Code (MDC, calculated from air temperature and precipitation; Girardin et al. 2013) and the Fire Season Length (FSL in days; Hély et al. 2010), representing the number of days with MDC > 300 (Lestienne et al. 2020a). Before 7000 yr cal BP, high MDC and FSL values indicate summer droughts conducive to fire. Thus, a combination of climate conditions favorable to fire and fuel availability may explain the frequent fires during the Early Holocene.

The second fire period extended from 5000 yr cal BP to the present. It followed a two-millennia-long period without fire, during which evergreen (*Q. ilex*-type) and deciduous (*Q. pubescens*) oak forests expanded, due to superior competitiveness (Colombaroli et al. 2009). After 5000 yr cal BP, landscapes became more open, and fire frequency and pollen-inferred biodiversity increased with the development of crops and pastures (Fig. 1). During this period, the fire signal varied locally (Lestienne et al. 2020b), and lower modeled MDC and FSL values (wetter conditions) support the hypothesis of an anthropogenic cause for the observed fire regime.

Future predictions

When comparing the Holocene fire hazard indices (MDC and FSL) with the predicted indices for the next eight decades and for two RCP scenarios (4.5 and 8.5), both scenarios show an increase until 2100, with a stronger increase in fire from 2050 using the RCP8.5 scenario (Fig. 2a; Lestienne et al. 2022). The MDC may increase from 424 to 456 (7% increase) for the RCP4.5 scenario and from 429 to 519 (17% increase) for RCP8.5 between 2020 and 2100. Accordingly, a lengthening of the fire season may also be expected (by 25–45 days, i.e. between 19% and 28%). This range of future lengthening of the fire season is in line with the 30 days estimated using previous climate simulations and fire indices (e.g. Giannakopoulos et al. 2005), but so far no study has proposed a Holocene framework for estimating and quantifying the significance of these future changes. Lestienne et al. (2022) showed that during the Holocene, such values (MDC > 400 and FSL > 100 days) have not been reached since 6000 yr cal BP, and the future FSL may exceed the Holocene maximum as early as 2040, regardless of the RCP scenario (Fig. 2b).

Our results also show that this global increase will most likely not be the same

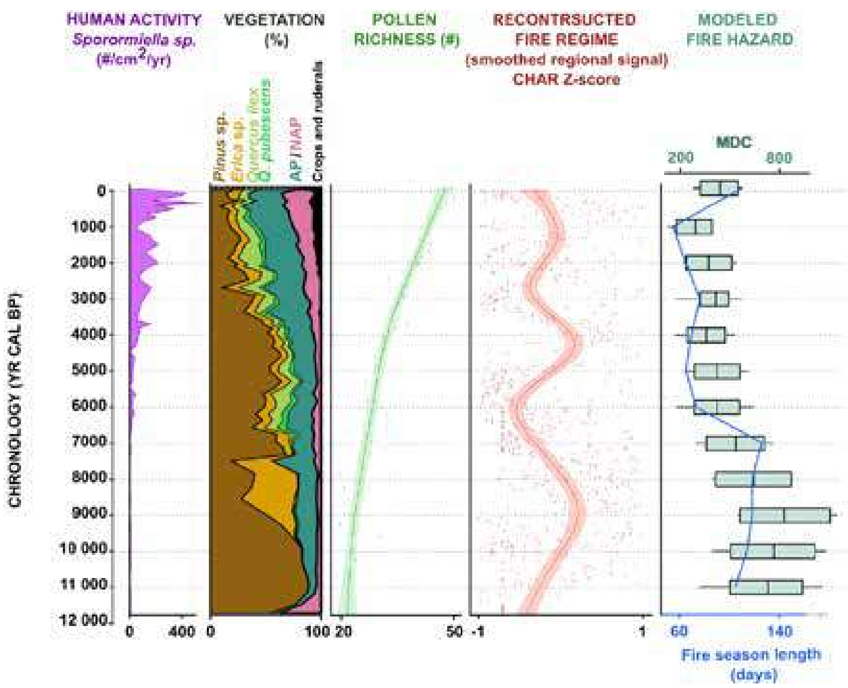

Figure 1: Synthesis diagram showing the history of human activity, vegetation diversity and fires (charcoal, Monthly Drought Code (MDC), and Fire Season Length (FSL)) in Corsica during the Holocene. The high levels in Sporormiella influx reflect human activity, particularly pasture. The pollen richness is used to evaluate vegetation diversity. A smoothed curve was generated from the resampled and rescaled (Z-score) CHAR values of the three lakes (Bastani, Nino, and Creno) using the LOESS (Locally Estimated Scatterplot Smoothing) method to reconstruct the fire signal. The MDC represents the fire-hazard intensity, while the FSL represents the fire-hazard duration. The two most active fire periods are highlighted in red; the second period is marked by more local signals (see Lestienne et al. 2020b).

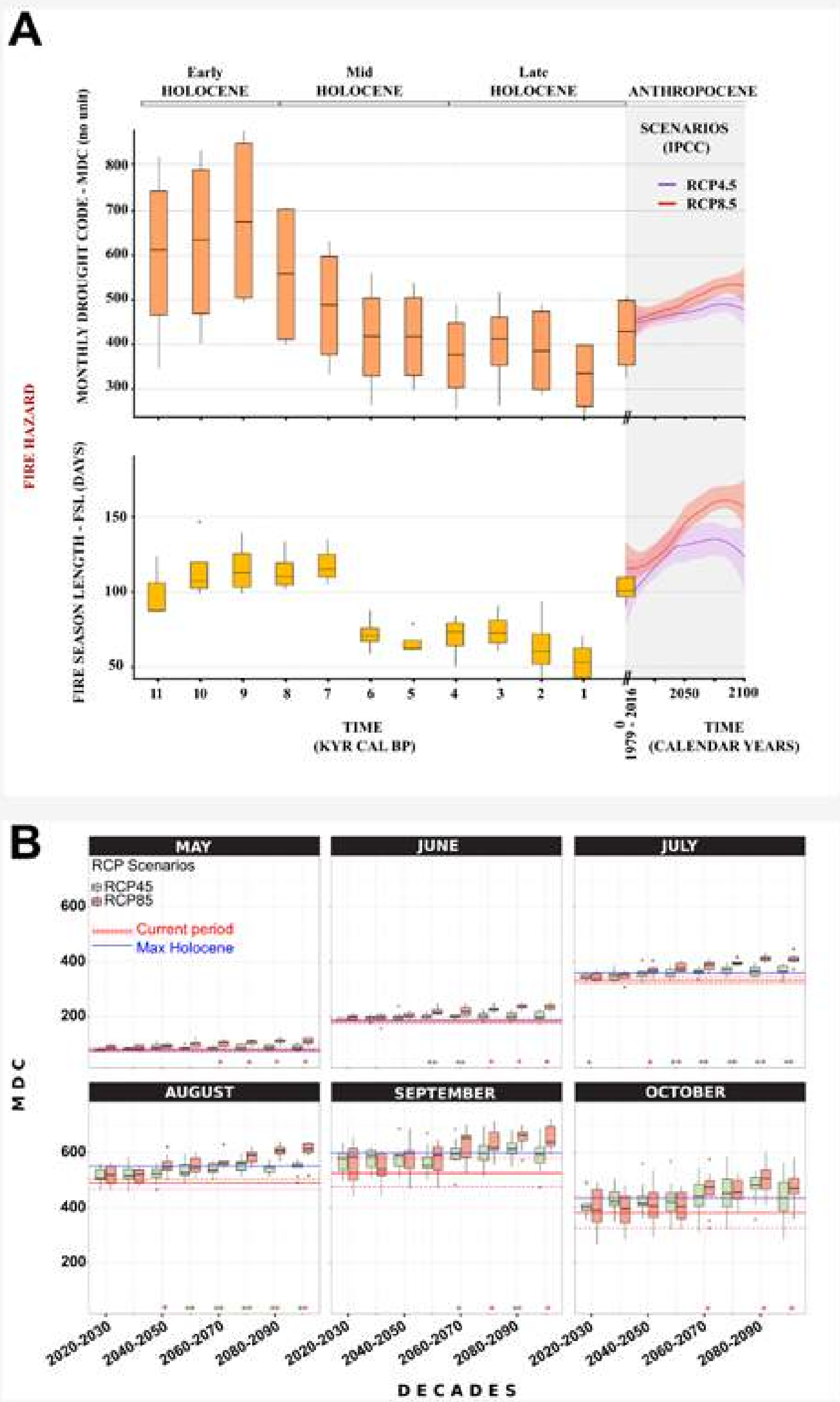

Figure 2: (A) Fire hazard changes in terms of Monthly Drought Code (MDC) and Fire Season Length (FSL) in Corsica during the Holocene and future decades. **(B)** MDC monthly means, by month, for the next decades. The blue line represents the maximum Holocene values, and the red lines represent the current means. Figure adapted from Lestienne et al. (2022).

for each month of the fire season (Fig. 2b; Lestienne et al. 2022): the MDC will reach its maximum during the summer months (June to August) with values higher than those observed during the Holocene maximum in both scenarios, and higher than historical means in the RCP8.5 scenario. The causes for this marked summer drying were investigated by Rowell and Jones (2006), who considered four possible mechanisms: (1) low soil-moisture conditions; (2) large land-sea contrast in warming conditions; (3) positive feedback from summer soil-moisture and precipitation; and (4) remote influences from teleconnections. These changes appear to be similar in both RCP scenarios until 2050 and will, therefore, depend on political and economic choices after 2050 (e.g. the use of green or fossil energy).

Our data suggest that the predicted increase in fire by 2050 will be significantly different from what Corsican ecosystems experienced during the Early Holocene, because other factors (including vegetation and human activities) also impact fire. Most studies agree that increasing drought will strongly contribute to increases in the frequency and intensity of forest fires in the Mediterranean, especially in southern France and Corsica (e.g. Mouillot et al. 2002). Our study complements these results by highlighting the increase in the duration of the fire season and intensification of the fire hazard.

A strong increase in fire occurrence, coupled with drier conditions, could lead to a significant decrease in plant biodiversity in Corsica (e.g. Lestienne et al. 2020b). Such ecological change would lead to significant economic losses (e.g. reduction in tourism). In France, the large fires in the 1990s led to the implementation of a very effective firefighting policy under weather conditions of the last decades (Curt and Frejaville 2018). However, this will likely be challenged by more extreme conditions in the coming years. Over the next 30 years, our current policies will also influence the climate response on longer timescales. Integrative studies combining modeling, long-term data records, and traditional fire knowledge can provide valuable insights to understand fire responses to complex vegetation–human–climate interactions, and support policy decisions in biodiversity hotspot regions such as Corsica.

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doi.org/10.22498/pages.30.1.48

Transforming tree-ring research through collaborations with Indigenous peoples

Kelsey Copes-Gerbitz[1], W. Spearing[2] and L.D. Daniels[1]

Integrating Indigenous knowledge into tree-ring fire histories without meaningful collaboration with Indigenous peoples is an ongoing form of colonization. Here, we describe how our collaborative tree-ring research process led to more accurate and ethical research expectations, questions, methods, and interpretations.

Tree-rings are valuable records of disturbance regimes that can guide landscape management by providing evidence of historical fire frequency, severity, extent, and drivers (Daniels et al. 2017). Tree-rings are often combined with other long-term proxy data (e.g. paleoecological records) for a more holistic understanding of historical fire dynamics (Swetnam et al. 1999). Increasingly, non-Indigenous natural scientists (including dendrochronologists) are also interested in incorporating Indigenous knowledge to help inform our understanding of historical fire dynamics (Guiterman et al. 2019; Larson et al. 2020; Roos et al. 2021). However, treating Indigenous knowledge as just another proxy record that must be validated by natural science overlooks the complex dimensions of Indigenous fire stewardship, such as spirituality, respect, and reciprocity (Lake and Christianson 2019). Furthermore, if not undertaken in collaboration with Indigenous peoples, tree-ring (and other paleoecological) research can perpetuate the power imbalances inherent in colonization by excluding Indigenous peoples from interpreting and managing landscapes (Mistry and Berardi 2016; Fernández-Llamazares et al. 2021). Here, we describe the evolution of our collaborative tree-ring research in British Columbia (BC), Canada, since 2016 as an archaeologist (WS) for the *T'exelc* (Williams Lake First Nation, an Indigenous community*) and as non-Indigenous natural scientists (KCG and LDD). This collaborative research took place at *Ne Sextsine*, a 6000-hectare forest in the *T'exelc* traditional territory that has been continuously stewarded since time immemorial.

Building a collaborative research context

Across BC, Indigenous fire stewardship was, and continues to be, spatiotemporally complex (Lake and Christianson 2019; Lewis et al. 2018). Nevertheless, over 100 years of colonial fire governance enacted on unceded Indigenous territories has excluded Indigenous peoples from decision-making, despite being strongly connected to place and invested in the future (Lake and Christianson 2019; Hoffman et al. accepted manuscript; Copes-Gerbitz et al. accepted manuscript). The legal implementation of the United Nations Declaration on the Rights of Indigenous Peoples in Canada and BC, however, provides an obligation to uphold Indigenous rights and advance reconciliation (Wong et al. 2020). Thus, as researchers in BC (KCG and LDD), it is our ethical duty to undertake collaborative tree-ring research with Indigenous peoples.

Our collaboration began on invitation from a non-Indigenous gatekeeper who is a well-respected member of the local community and undertakes forest management guided by Indigenous and natural science. This gatekeeper was familiar with our tree-ring fire histories and was entrusted by the *T'exelc* to manage *Ne Sextsine*. In 2016, this gatekeeper introduced us (KCG and LDD) to the elected Chief and Council, who then introduced us to members of the Natural Resources Department, including an archaeologist (WS), who became a key collaborator, and the Elder Council. All groups expressed interest in building a research collaboration. Through eight community meetings and six months spent in the community over the next three years (by KCG), we co-developed our research questions guided by the interests of Elders and forest managers – including, but not limited to, how Indigenous land and fire stewardship shaped the historical landscape through time and how this stewardship can inform future management. Our agreed research practices, including guiding questions, data ownership and confidentiality, and expectations of researchers (such as publications), were outlined in a signed Memorandum of Understanding between the elected *T'exelc* Chief, the *Ne Sextsine* forest manager, and the researchers. At the time, this level of engagement was beyond the requirements of our university's research ethics process, but we felt it was imperative for maintaining reciprocal trust and respect. Today, researchers at the University of British Columbia are required to formalize legally binding agreements with Indigenous community partners before collaborative research can begin.

Co-developing sampling methods

A key element of our collaborative research was co-developing data collection methods (Wong et al. 2020). Tree-ring research is inherently extractive because we access land and collect, remove, and usually archive material at research institutions. To address this challenge, the sampling methods were guided by archaeological best practice (by WS) and the *T'exelc* Elders. This included avoiding culturally modified trees and archaeological sites that are protected by the BC Forest and Range Practices Act and the Heritage Conservation Act. However, these legal frameworks have limitations, such as no protection for sites dating after 1846 (the year in which BC claimed sovereignty) and a lack of comprehensive site records (Schaepe et al. 2020). Given these limitations, WS and the Elders specifically provided permission

Figure 1: Fire-scarred tree with at least 12 visible fire scars at *Ne Sextsine*. Although this tree could have been "convenience" sampled, we intentionally left it intact as it was the sole fire-scarred tree located along an important travel corridor for the *T'exelc* (photo credit: Kelsey Copes-Gerbitz).

*The Constitution of Canada recognizes three groups of Indigenous peoples, including First Nations, Métis, and Inuit.

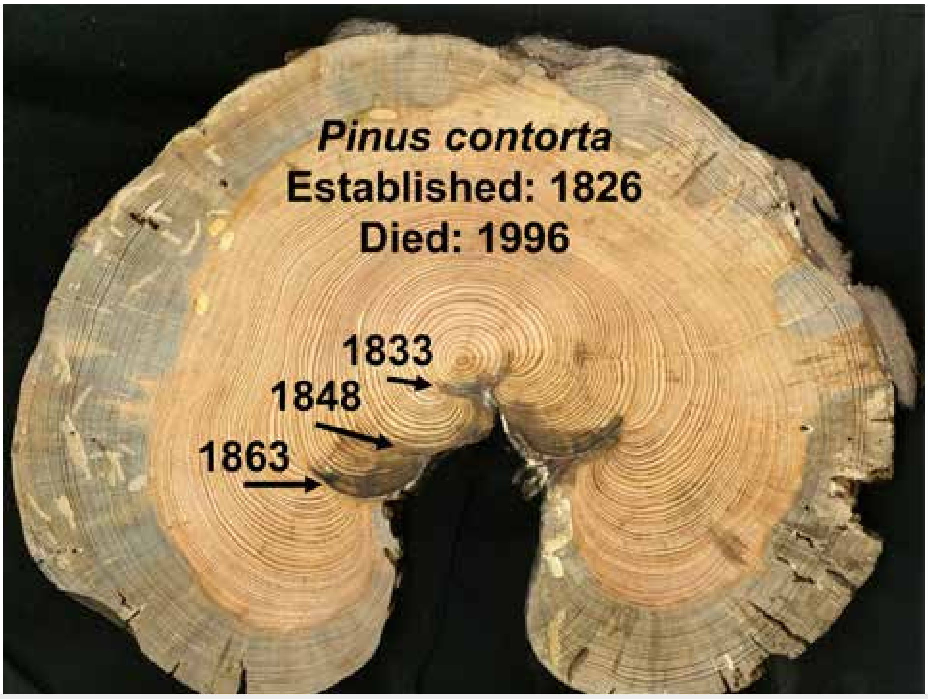

Figure 2: Tree with fire scars in 1833, 1848, and 1863. A distinct lack of fire after 1863 is a result of colonization, the stories of which were shared by Elders through our collaboration (Copes-Gerbitz et al. 2021) (photo credit: Kelsey Copes-Gerbitz).

to sample in areas that were culturally important, but not protected by law. WS also developed a protocol for KCG to simultaneously inventory potential archaeological sites given our systematic sampling across *Ne Sextsine*.

One primary conundrum was how to ethically sample fire-scarred trees. If a fire scar has formed because of Indigenous ignitions, does that make it a legally protected, culturally modified tree? Advice given to WS suggested there are no legal protections–but we agreed that it may be unethical to sample without attending to cultural values. Through our collaboration, we learned that the intentional use of landscape fire at *Ne Sextsine* was considered a "lost practice" by Elders (Copes-Gerbitz et al. 2021), such that we would not know the location of intentional fires in advance of sampling. Instead, based on WS's guidance, the researchers prioritized dead trees (stumps, logs, and snags) for sampling, and received permission from WS for each partial section of a live tree (Cochrane and Daniels 2008). Ultimately, we left approximately 80% (n = 43) of live trees with visible fire scars untouched, including one site that was excluded from sampling, to ensure we did not disturb any archaeological sites or potentially unique cultural trees (Fig. 1). The digital archive of scanned samples will be held by both the researchers and the *T'exelc*, while the physical fire scar samples will be returned to *T'exelc* care. This reflexive sampling approach ensured that we upheld our ethical commitments, exceeding legal responsibilities.

Interpretations grounded in our collaboration

In our opinion, a key outcome of this collaboration was the way in which it guided our interpretation of the fire history and management recommendations. We learned directly from the Elders who spent their youth at *Ne Sextsine* about diverse values that underpinned their enduring connection to place (Copes-Gerbitz et al. 2021). These values, and the stewardship used to maintain them, inevitably shaped the fire history embedded in the tree-rings. Thus, our interpretations do not rely solely on quantitative fire history metrics (such as frequency and severity) or on discounting other potential fire regime controls (such as fuels, topography, or climate). Rather, we center the Elders' stories and highlight the ways in which colonization interrupted the spatiotemporally heterogenous *T'exelc* stewardship (Fig. 2; Copes-Gerbitz et al. unpublished manuscript). This interpretation ensured that Indigenous knowledge and natural science were both important ways of understanding fire history and avoided the pitfalls of potentially erasing the complexity of Indigenous fire stewardship if it is subsumed into natural science research (Bohensky and Maru 2011). Furthermore, in our collaboration, we followed principles from an action-oriented approach known as "walking on two legs" that helps natural scientists support Indigenous-led restoration of fire-adapted landscapes (Dickson-Hoyle et al. 2021). Ultimately, our management recommendations stress the importance of returning *T'exelc* stewardship and decision-making to *Ne Sextsine*.

On reflection, our collaboration helped more accurately and ethically interpret the historical fire regime recorded in tree-rings. It also enriched the history of *Ne Sextsine*, complementing *T'exelc* Elders' stories with tree-rings and providing a foundation for future archaeological investigations, such as where physical evidence no longer remains (e.g. summer fishing camps and berry patches), but oral stories and tree-rings indicate occupation prior to 1846. Importantly, it also helped the Elders reconnect with a meaningful place that many had not visited in decades (Copes-Gerbitz et al. 2021). Our collaboration was indeed a reflexive and iterative process, not a checklist that can be applied directly to other collaborations or contexts. However, as other researchers have done (Mistry and Berardi 2016; Wong et al. 2020; Dickson-Hoyle et al. 2021), we emphasize the importance of humility, respect, and long-term, ongoing trust-building as central elements of our research collaboration. We continue to have much to learn from the original Indigenous stewards and are grateful for their generosity in sharing their wisdom.

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doi.org/10.22498/pages.30.1.50

"Working with": The ethics and practices of engaging Indigenous peoples in scientific research

Kayla M. de Freitas[1,2], G.A. Winter[3], T. A. Kennedy[3,4], A. Johnny[3,4] and J. Mistry[1,2]

Indigenous peoples' contribution to science is increasingly recognized in academia. Cross-disciplinary approaches in past environmental change research provides a holistic picture of climate and justice issues. There needs to be ethical engagement of Indigenous peoples in research, with two-way benefits.

Indigenous peoples' contribution to scientific research is increasingly recognized in academia, policy, climate change research, and conservation management (Delgado et al. 2017; Hill et al. 2020). Past environmental change research combined with traditional knowledge can provide innovative perspectives to conservation, climate impact and justice issues (Lyver et al. 2015). By working with Indigenous peoples, paleo-ecological scientists can enhance their data collection and analysis, but also contribute results that support Indigenous rights and management decisions. To meaningfully engage with Indigenous peoples, academia needs to encourage approaches that engage with diverse knowledge systems.

Here we outline the increasing recognition of Indigenous people's contributions to academia. This is followed by the ethics of engagement recommended by Indigenous researchers themselves, and finally we examine the "two-way" relationship between "researcher" and "participant" covering issues such as data ownership and benefits, and its relevance to paleoecological researchers.

Indigenous contribution to scientific research, environmental policy, and management

Current scientific research is rooted in curiosity and the need to find innovative solutions in today's rapidly changing climatic, economic, environmental, and ecological circumstances. Scientific research, historically and currently, relies on Indigenous knowledge in many aspects of fieldwork and research. This contribution and collaboration has not always been accredited, but, today there is increasing recognition of Indigenous knowledge in academia and among practitioners who work with diverse knowledge systems (Delgado et al. 2017). This recognition is across fields in different disciplines and includes, but is not limited to: climate change adaptation and risk reduction (Mercer et al. 2010), biodiversity conservation (Robinson and Wallington 2012), and environmental policy and landscape management (Milgin et al. 2000; Hill et al. 2020).

Top-down environmental policies often clash with realities on the ground; for example, in Canaima National Park, Venezuela, fire suppression policies led to increased occurrences of destructive fires and marginalization of the Indigenous Pemon land management techniques using patch burning in a flammable landscape (Bilbao et al. 2010). Thus, there is an increasing need to support the development of appropriate policies that integrate local governance systems and ways of making decisions about environmental management (Delgado-Serrano et al. 2017).

There are tensions surrounding the engagement of Indigenous peoples in scientific research; namely, these tensions surround issues of ethical engagement, data sharing, acknowledgement of contribution, and benefits for Indigenous peoples in providing support to science.

Ethics of approaching and engaging Indigenous peoples in research

Engagement with Indigenous peoples can lead to a more holistic understanding of land-use practices, but also creates a risk for perpetuating colonial approaches. Merging paleoecology, archaeology, and oral histories can support Indigenous land struggles (Oetelaar 2002; Hogg and Welch 2020). Paleoecology provides past environmental data about land that people occupy and use, which can contribute to decisions regarding land management for the future. These types of data can strengthen claims to land, showing historical use of customary lands, and can aid in presenting a case to the government and relevant authorities, but challenges exist regarding how this can be done in an ethical manner (Chilisa 2020).

Indigenous representatives and allies have raised questions about data governance and advocated for research that benefits Indigenous agendas and needs (Tsosie et al. 2021). Some researchers have diversified their methodologies, using more participatory approaches such as participatory video, where participants in research create their own films about the issues or topics they are concerned with as part of a collaborative approach with the researcher. These new approaches have the potential to transform collaboration, put the research process more in the hands of Indigenous peoples, and be used to assert identity and raise awareness on issues such as land rights (Mistry et al. 2015).

Some Indigenous representative organizations, like the South Rupununi District Council (SRDC) in Guyana, have created internal guidelines on how researchers, and others seeking to work with Indigenous communities, should ethically engage. Key messages include the need for contemporary research with Indigenous peoples to engage on principles of trust and relationship building, reciprocity, and clarity on what results from the research will be used, and who will be acknowledged as owners of the final product. A local grassroots conservation organization, the South Rupununi Conservation Society's (SRCS) approach incorporates local design and initiatives in planning for conservation activities.

Figure 1: Conscious research ensures that the process is not "academic mining", but respectful and active engagement. By ethically engaging with Indigenous peoples, researchers in paleoecology, and related fields, can enhance scientific research by working with diverse systems and considering innovative approaches to tackling today's environmental issues, but also contribute to Indigenous rights and self-determination (photo credit: Angelbert Johnny/South Rupununi District Council).

Community Researcher Rangers are trained to collect data in support of their conservation activities on their customary lands, help design research approaches, and identify what key areas the SRCS should focus on.

Steps to encourage ethical engagement with Indigenous peoples

For the steps outlined in Table 1, the principles of Free, Prior, and Informed Consent (FPIC) should continuously be employed throughout engagement with Indigenous peoples (see ohchr.org/en/indigenous-peoples for more information).

Table 1 summarizes a guide for ethically engaging with Indigenous peoples, one of the outcomes of a webinar promoted by the PAGES DiverseK working group and the Leverhulme Wildfires Centre (pastglobalchanges.org/calendar/128488).

A two-way relationship: Data ownership and benefit sharing

Kwaymullina (2016) states that there are three "thresholds" that non-Indigenous scholars should take into consideration when thinking about working with Indigenous peoples: if the research should be conducted, power dynamics and impact of the fieldwork, and the ethical principles, such as FPIC and intellectual property rights, used in research. Researchers who benefit from Indigenous knowledge and experience, or rely on Indigenous peoples' support in data collection, have a responsibility to ensure ethical engagement during research, appropriate methodologies to approach research with Indigenous peoples, and clarity on data ownership and who benefits from what aspects of the research (Tsosie et al. 2021). Indigenous peoples have historically been misrepresented in research, and steps to correct this have been taken in the form of acknowledgement or co-authorship on manuscripts (Smylie et al. 2020).

The co-production of knowledge through research with Indigenous peoples should be based on trust and agreed reciprocity (Milgin et al. 2000; Carroll et al. 2020). This is a process that takes time, and researchers' expectations for timelines must be adapted to allow for authentic engagement with Indigenous communities. Researchers often have their own aims to achieve and should consider what is meant by a "two-way" relationship. Thus, the expectations for researchers working with diverse knowledge systems within academia should be adjusted to reflect this. Paleoecologists and other scientists can strive to engage in research that builds local capacity, encourages local governance, contributes data towards Indigenous peoples' needs, and create a space for local decisions. For example, shown in Figure 1, within the SRDC there are people who create maps for their own territory that are used in land-rights discussions or management planning as a product of engaging in previous research that promoted skills and knowledge exchange.

Before the research

- Be familiar with the cultural and environmental context of chosen research site.
- Contact community to introduce self and ideas, and to seek consent.
- Share research idea/topic and engage in discussion to collaboratively design research question and methodology.
- Be clear which data will be collected, how they will be collected, and how they will be used.
- Negotiate and be clear on who owns what data, and which data can be published or kept for community use.
- Negotiate to determine appropriate compensation for research assistants and the community.
- Understand and respect existing processes for permission and data ownership in the community.
- Acquire all other necessary permits nationally.

During the research

- Make knowledge and skill exchange part of your approach.
- Spend quality time in the community, building trust and understanding of customary systems.
- Be flexible in your methodology; if you are working with more than one community, they may not all want to be engaged in the same way. FPIC is a continuous process, and there should be opportunities for people to ask questions throughout the research.

After the research

- Validate your results at a community meeting. Share preliminary results and ensure that the community agrees that what you have collected or discerned is correct.
- Make final agreements on how to properly acknowledge assistants and the community.
- Make final agreements on data sharing; if no data storage system exists in community, share your data in multiple formats: for example, in-person presentations, brochures, audio recordings explaining the results, and/or a hard copy of the research.

Table 1: Steps to encourage ethical engagement

ACKNOWLEDGEMENTS

This contribution reflects discussions during a PAGES DiverseK webinar presentation in September 2021 (pastglobalchanges.org/calendar/128488) by three Indigenous researchers from the South Rupununi, Guyana (co-authors of this article: GAW, TAK, and AJ), who spoke of their experiences working with scientific researchers. The webinar sought to create a space for interaction between Indigenous researchers from the South Rupununi District Council (SRDC) the South Rupununi Conservation Society (SRCS) and other scientific researchers. In particular, the webinar targeted scientists in the field of paleoecology interested in undertaking work with Indigenous peoples. Watch the recording at vimeo.com/662695164.

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doi.org/10.22498/pages.30.1.52

Phase 4 of the PAGES 2k Network: Hydroclimate of the Common Era

PAGES 2k Network coordinators*

The PAGES 2k Network (pastglobalchanges.org/2k), founded in 2008, is one of the longest-running PAGES working groups. It has consistently achieved a high degree of community engagement and delivered significant datasets and publications. These have fundamentally improved our understanding of global climate changes through the Common Era. The 2k reconstructions of global temperature variability were featured in Figure 1 of the Summary for Policymakers of the IPCC's Working Group I contribution to the Sixth Assessment Report (AR6; IPCC 2021).

Along with temperature, hydroclimate is an important way in which societies experience climate variability. However, AR6 highlighted notable uncertainty in historical (Fig. 1) and projected hydroclimate changes, and low agreement on the regional scale (Fig. 1). Constraining the models used to simulate future changes, and using these same models to provide dynamical understanding of past hydroclimate, are therefore the main foci of the new (4th) phase of the 2k Network.

Phase 2 of the 2k Network (2014–2016) provided recommendations for incorporating paleoenvironmental data and climate model simulations to understand hydroclimate (PAGES Hydro2k Consortium 2017). Building on this, Phase 3 (2017–2021) supported the development of new databases, including:

- Iso2k (pastglobalchanges.org/iso2k), a compilation of proxy records preserving information of hydroclimate changes via their imprint in the stable isotopic composition of water;
- CoralHydro2k (pastglobalchanges.org/coralhydro2k), a collection of paired coral $\delta^{18}O$ and Sr/Ca records that can be used to investigate temperature and hydrologic variability in the tropical to subtropical oceans; and
- CLIVASH2k (pastglobalchanges.org/clivash2k), a collection of ice core proxies to understand southern hemispheric climate modes.

These 2k Network products, and other data compilations, contain extensive information about hydroclimate-relevant variables (e.g. precipitation amount, the ratio of precipitation to evaporation, atmospheric circulation patterns, drought, floods, and seawater characteristics). Hydroclimate changes are inherently more complex than temperature changes, which motivates the science goals of the new phase.

Scientific goals

Phase 4 of the 2k Network builds on previous and ongoing projects, as well as modeling and data synthesis and assimilation activities within the wider paleoclimate community, to better understand Common Era hydroclimate by working on the following objectives:

- Leverage paleoclimate proxy information contained in ongoing and existing databases (e.g. Iso2k, CoralHydro2k, CLIVASH2k, drought atlases, Neotoma, SISAL), and datasets not yet collated in databases, to understand spatial and temporal hydroclimate variability. This includes developing a better understanding of uncertainties.
- Use the hydroclimate proxy and reconstruction data to evaluate Earth system models, whilst using these models to inform process-level understanding of Common Era hydroclimate. This includes close integration with the modeling communities.
- Ensure that 2k Network data products are available for ongoing use through dedicated tools and practices to maximize their longevity and interoperability.
- Work with policy advisors to ensure that 2k Network scientific findings will be used to inform policy outcomes.

Invitation to engage in Phase 4 activities

To achieve our aims, the coordinators will facilitate interaction among researchers. This includes liaising with ongoing 2k research efforts as well as partner research groups and external stakeholders, e.g. CVAS (pastglobalchanges.org/cvas), SISAL (pastglobalchanges.org/sisal), Floods (pastglobalchanges.org/floods), PMIP-Past2k (pmip.lsce.ipsl.fr/working_groups/Past2K), LinkedEarth (linked.earth), and WCRP Lighthouse Activities (wcrp-climate.org/lha-overview). We are particularly interested in participation from the modeling community to ensure that we collate hydroclimate proxy data that enables meaningful comparison with climate model outputs. We invite researchers that participate in these groups to contact us if they would like to be a formal liaison.

Interactions facilitated by the 2k Network will include workshops, a continuation of the successful online 2k seminar series, and engagement with early-career researchers (ECR). The first workshop will be held as a splinter meeting of the PAGES OSM (May 2022). This workshop will scope what steps are required to mine hydroclimate-relevant information from existing databases, identify data that are not yet in databases, and connect to data assimilation and climate simulation efforts. A second workshop will focus on data-model integration, including proxy system model steps, and a third workshop will develop tools to ease data re-use and interoperability. The PAGES 2k coordinators will apply for a PAGES Data Stewardship Scholarship (following up on three successful 2k Network-related proposals in 2021) and additional funding. We invite researchers to get in touch if interested in giving a seminar (or with topics that you would be interested in hearing about!), to participate in database compilation, and if specific workshop themes are of interest. We also aim to enable discussion on data accessibility and software tools through dedicated projects with the ECR and LinkedEarth communities.

To succeed in our plans, the 2k Network relies on the engagement of the wider community. We are excited to invite you to our first Phase 4 virtual workshop to be organized online at the PAGES Open Science Meeting (pages-osm.org) in May 2022.

Figure 1: This photograph was taken a few days after a forest fire in a pine-forested area near Montellano (SW Spain) (photo credit: Antonio Jordán, University of Seville, Spain; imaggeo.egu.eu/view/1327). License: CC BY-NC-SA 3.0 (creativecommons.org/licenses/by-nc-sa/3.0).

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doi.org/10.22498/pages.30.1.53

The second phase of the Cycle of Sea-Ice Dynamics in the Earth System (C-SIDE) working group

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Antarctic sea ice plays several crucial roles within the Earth system. The sea-ice seasonal cycle influences atmospheric dynamics (heat and air-sea gas exchanges; Rysgaard et al. 2011) and affects the circulation of heat, salt, and nutrients within the ocean (Maksym 2019). On glacial–interglacial timescales, sea ice has been proposed as an important player in modulating changes in atmospheric carbon dioxide concentration (Kohfeld and Chase 2017). Our understanding of the role of sea ice within this system is dependent on our ability to reconstruct and model past sea-ice changes, as well as to reconstruct and model complementary changes within the Earth and climate system.

The Cycles of Sea-Ice Dynamics in the Earth System (C-SIDE; pastglobalchanges.org/c-side) working group was established in 2018 to synthesize existing sea-ice records from the Southern Ocean over the past 130,000 years. The main objective of C-SIDE is to better understand how changes in sea ice were related to other important oceanic processes, and to examine more closely how sea ice is simulated in Earth system model simulations of the last glacial period. Our choice of this timescale was selected so that we could evaluate sea-ice dynamics during previous warm periods (e.g. the Last Interglacial Period when Antarctica was 2°C warmer than today), warming glacial-to-interglacial transitions, and the major cooling periods of glacial inception, during which ocean carbon uptake was substantial.

During our first three years, the C-SIDE group held two workshops with the sea-ice community, which helped us to establish research priorities and outline the scope of our efforts. We assembled a comprehensive inventory of Southern Ocean sea-ice records covering at least a part of the time interval between 130,000 years ago and the Holocene. From this inventory, we identified 24 sites with high-resolution and long-duration sea-ice records for the last glacial-interglacial cycle (Fig. 1; Chadwick et al. 2022b). These data have been submitted to the PANGAEA database, and the paper has been submitted as part of a special issue that we organized for *Climate of the Past* entitled "Reconstructing Southern Ocean sea-ice dynamics on glacial-to-historical timescales". This special issue will be accepting topical submissions until December 2022. In addition to the sea-ice compilation, this special issue includes articles presenting new Southern Ocean sea-ice reconstructions (Chadwick et al. 2022a; Jones et al. 2022), as well as articles discussing developments in novel Antarctic sea-ice proxies (Lamping et al. 2021; McClymont et al. 2022; Vorrath et al. 2020). It also contains articles evaluating the processes controlling sea-ice distribution and deep-ocean circulation in simulations of the last glacial maximum, using climate models from the Paleoclimate Modelling Intercomparison Project PMIP3 and PMIP4, and iLOVECLIM (Lhardy et al. 2021; Green et al. 2020).

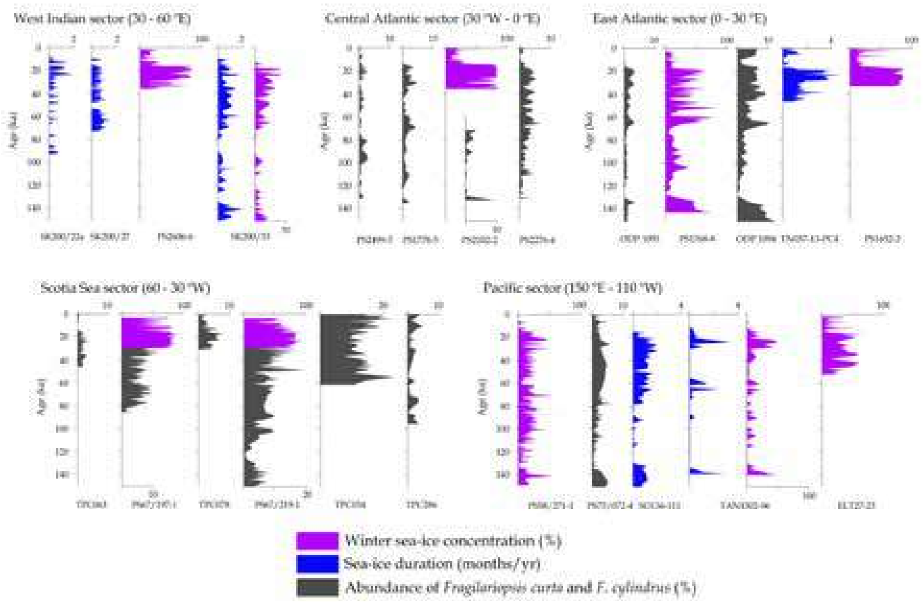

Figure 1: Compilation of Southern Ocean sea-ice records for the last 150,000 years from 24 core sites. Sea-ice records are grouped by region of the Southern Ocean and colored according to sea-ice reconstruction type. This figure is adapted from Chadwick et al. (2022b).

The second phase of the working group is already brimming with activities. Two review papers are nearing completion and will address, firstly, the use of a range of proxies for reconstructing sea ice during the last 130,000 years and, secondly, the current state of our understanding of how sea ice is linked with atmospheric, oceanic, land ice, and biogeochemical processes on glacial–interglacial timescales. With the help of funds from Simon Fraser University (SFU) and the Canadian Mitacs program, C-SIDE members will be hosting three early-career researchers at SFU to bring together complementary datasets (sea-surface and subsurface temperature records reconstructed using radiolarian proxies) to examine temporal relationships between sea-ice changes and ocean temperature and water mass behavior in the Southern Ocean. C-SIDE is also collaborating with the leaders of the Arctic Cryosphere Change and Coastal Marine Ecosystems (ACME; pastglobalchanges.org/acme) working group to produce a PAGES Magazine issue on sea-ice changes at both poles to be published in the second half of 2022. Finally, as international travel possibilities re-emerge, the C-SIDE steering committee is looking into opportunities to reschedule our third, postponed, workshop, to focus our ongoing efforts within the global sea-ice and PAGES communities.

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doi.org/10.22498/pages.30.1.54

Q-MARE working group

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Climate and human activities altered marine ecosystems for thousands of years before industrialization, changing the structure and dynamics of marine communities, and the distribution, ecology, and physiology of marine organisms (e.g. Jackson 2001; Engelhard et al. 2016). However, disentangling these impacts from those of natural climate variability (Kowalewski et al. 2015; Agiadi et al. 2018), remains a challenge. Pre-industrial baselines are, therefore, necessary to understand the true magnitude and rate of change induced by modern anthropogenic activities, including climate change.

Q-MARE (pastglobalchanges.org/q-mare) brings together scientists from vastly different disciplines, including historians, archaeologists, paleontologists, and ecologists, to explore the impacts of climate and human activities on the environment during the pre-industrial era. Time series from scientific monitoring postdate the industrial revolution. Therefore, our working group relies on a variety of tools for reconstructing patterns of biodiversity loss and ecosystem resilience. Moreover, we aim to provide guidelines for the integration of multidisciplinary observation data and proxy-based reconstructions with dynamic ecosystem models.

Scientific goals and objectives

How did climate and human activities affect marine ecosystems in the pre-industrial Holocene and the Pleistocene? Fossil and death assemblages provide data on both exploited and unexploited species. However, these archives have been a largely untapped resource for disentangling the relative contributions of climate and human activities on biota. Disproportionate changes in abundance and/or disappearances of exploited species reflect human impacts (Dillon et al. 2021), whereas climatic changes show effects across species (Albano et al. 2021). Such selective changes are visible in the stratigraphic record and can be interpreted along with paleoclimatic, archaeological, and historical records.

When did humans start having a significant impact on the marine environment? Historical, archaeological, and sedimentary records will be combined to construct a database that will then be used to identify some of the first human impacts and their causes. In addition, pivotal studies on the importance of quantifying ecological baselines will be revisited, considering new knowledge on the timing of the first human settlements and medium-to-large-scale marine resource exploitation in different regions, and their possible impacts on the natural environment (Engelhard et al. 2016; Holm et al. 2022).

How can data from different sources be combined to inform environmental conservation targets and model marine ecosystems? We aim to provide clear solutions to the methodological issues and guidelines for accessing, processing, and analyzing data derived from different sources (paleontological, archaeological, and historical) and integrating them into dynamic ecosystem models, such as dynamic food-web models, for disentangling human and climate impacts.

Visit the Q-MARE website at pastglobalchanges.org/q-mare and sign up to our mailing list to receive news and updates on our activities.

Upcoming activities

The first Q-MARE meeting was held 17–19 January 2022 online (pastglobalchanges.org/calendar/128791). Our next events will be a workshop on "Quaternary marine ecosystems" (December 2022) and a group meeting in early 2023 (both online), an in-person stakeholder engagement meeting in late 2023, and a training workshop in 2024.

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Figure 1: Raking for Holocene shells in the Bahamas (photo credit: Tobias Grun, University of Florida).

doi.org/10.22498/pages.30.1.55

Expanding PlioVAR to PlioMioVAR

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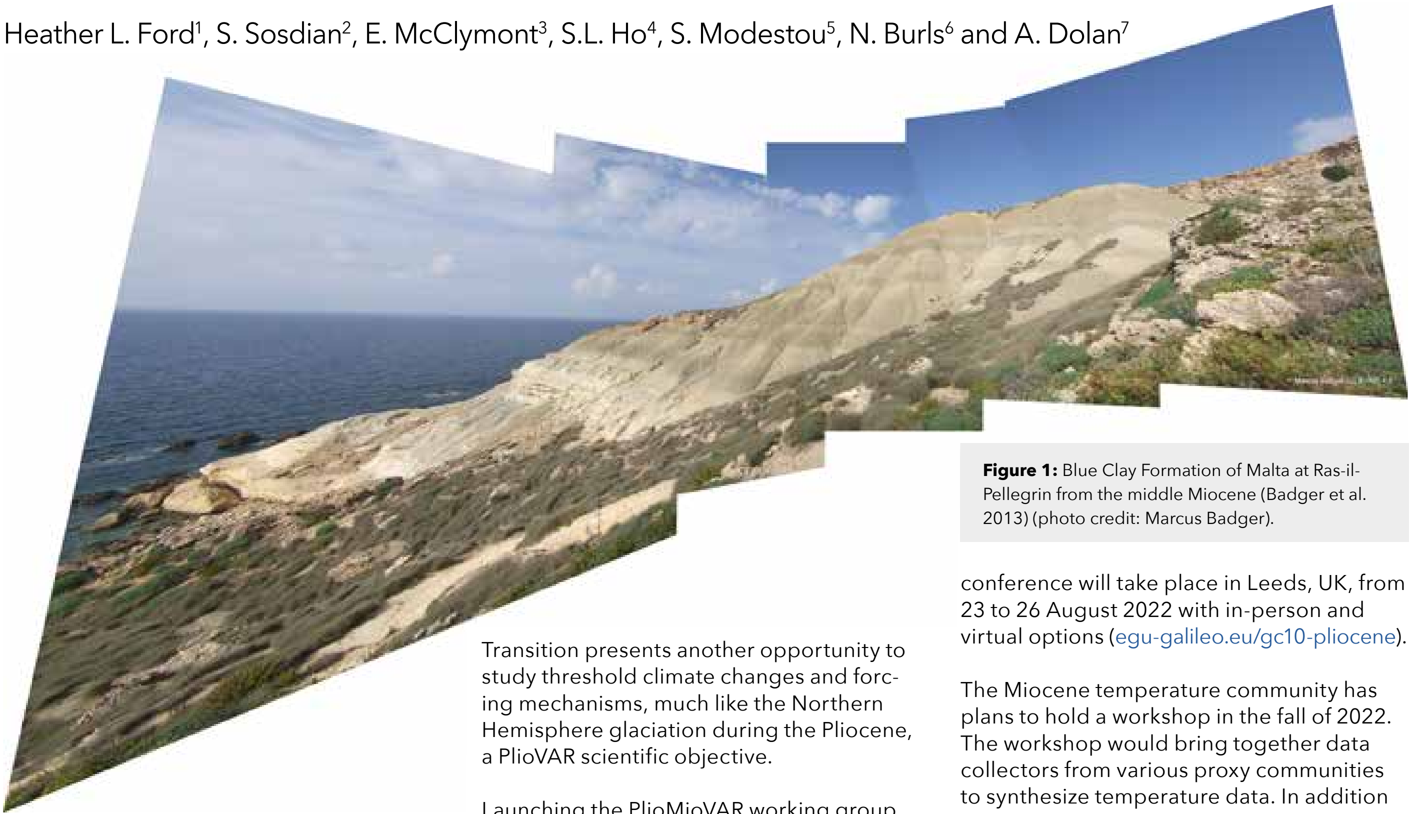

Figure 1: Blue Clay Formation of Malta at Ras-il-Pellegrin from the middle Miocene (Badger et al. 2013) (photo credit: Marcus Badger).

Reconstructions of past major transitions and warm climate states are critical for evaluating future climate projections under high greenhouse gas forcing. This working group aims to build on the success of the PAGES working group Pliocene climate variability over glacial-interglacial timescales (PlioVAR; pastglobalchanges.org/pliovar) to include the Miocene and form PlioMioVAR (pastglobalchanges.org/pliomiovar).

For decades the mid-Pliocene warm period has been a data-model comparison target (United States Geological Survery PRISM, PlioVAR, and Pliocene Model Intercomparison Project (PlioMIP); Haywood et el. 2020). During the mid-Pliocene warm period (~3.2 Myr BP), global temperatures are estimated to have been ~2.3°C warmer than today (McClymont et al. 2020) and atmospheric CO_2 is estimated at ~394–330 ppm (de la Vega et al. 2020). However, as modern atmospheric concentrations rise above 410 ppm, it is increasingly necessary to expand our efforts to other periods of sustained warmth.

Expanding interest in Miocene research (~23.03 to 5.33 Myr BP; Lawrence et al. 2021; Burls et al. 2021) includes the mid-Miocene Climate Optimum which is another globally warm equilibrium climate state for data–model comparisons when atmospheric CO_2 was higher than today (~600 ppm; Sosdian et al. 2018). Additionally, the ice-sheet expansion and cooling of the mid-Miocene Climate Transition presents another opportunity to study threshold climate changes and forcing mechanisms, much like the Northern Hemisphere glaciation during the Pliocene, a PlioVAR scientific objective.

Launching the PlioMioVAR working group will provide a framework for sharing best practices in community-wide engagement, database building and data-model comparison.

Scientific goals and objectives

The PlioMioVAR working group has three main goals. The first is to maintain the existing PlioVAR database and expand to the Miocene by synthesizing climate records and including age-model quality metadata. This will help identify the Miocene target for data-model comparison (likely the Miocene Climate Optimum) and identify gaps in our current Miocene paleoclimate records (temporal resolution, spatial coverage, proxy confidence). The second is to explore new data-model comparison studies to characterize climate variability including transient model simulations and coupled models with biogeochemistry. The third is to compare the long-term evolution of Pliocene and Miocene climate and consider forcing mechanisms like tectonic gateways or CO_2.

Planned workshops

EGU Galileo Conference "The warm Pliocene: Bridging the geological data and modeling communities", with funding from UKIODP and PAGES, is scheduled in August 2022. In addition to presenting the major achievements of PlioVAR, PlioMIP and the rest of the Pliocene community, this workshop will include discussions on launching PlioMIP3, developing synergy between the PlioMIP3 and PlioMioVAR community and strategizing community engagement with the IODP 2050 Science Framework. The conference will take place in Leeds, UK, from 23 to 26 August 2022 with in-person and virtual options (egu-galileo.eu/gc10-pliocene).

The Miocene temperature community has plans to hold a workshop in the fall of 2022. The workshop would bring together data collectors from various proxy communities to synthesize temperature data. In addition to examining best approaches to a global temperature reconstruction and exploring regional and global temperature patterns, another goal of this workshop is to develop a plan for providing useful output for the modeling community.

Visit the PlioMioVAR website at pastglobalchanges.org/pliomiovar and sign up to our mailing list to keep up to date with our activities. Updates on complimentary Pliocene and Miocene modeling efforts can be found at geology.er.usgs.gov/egpsc/prism/7_pliomip2.html and deepmip.org/deepmip-miocene, respectively.

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doi.org/10.22498/pages.30.1.56

Towards reliable proxy-based reconstructions: Community perspectives and criteria for the ACME database

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1st ACME workshop, Hanko, Finland, 25-27 October 2021

Arctic coastal ecosystems, vital for both Arctic species and people, are facing marked changes due to impacts of recent climate warming. To contextualize current changes, and to better anticipate future trends, long-term reference ecological data are needed. Marine sedimentary proxies can elucidate past ecosystems, and are widely used as tools to reconstruct past conditions. However, these tools need to be robust and reliable to ensure accurate estimations of ecological changes in nearshore Arctic ecosystems. Our present understanding and calibration of Arctic marine proxies stems predominantly from open ocean settings. Therefore, more work is needed to assess, refine, and develop marine proxies, including: benchmarking and harmonizing techniques and protocols; understanding proxy formation and behavior; and quality controlling available datasets.

In October 2021, the working group Arctic Cryosphere Change and Coastal Marine Ecosystems (ACME; pastglobalchanges.org/acme) held its first workshop, with a total of 22 participants joining either physically in Finland (Tvärminne research station) or online (pastglobalchanges.org/calendar/26994). The workshop aimed to evaluate the applicability of marine sedimentary proxies commonly used for paleo-reconstructions in Arctic nearshore environments, and to establish community-defined criteria for database entries. From October to November 2019, ACME conducted a survey to inform this workshop, collecting perspectives on the current state and future directions of Arctic coastal paleoceanography in order to: (1) outline priority research questions and directions; and (2) provide an overview of spatial, methodological, and ecological knowledge gaps.

The two-day meeting began with discussing results of the survey, which included five open questions and 22 multiple choice questions within the scope of three themes: status of proxy understanding in Arctic marine/coastal environments; data handling and statistical practices; and study design and community integrity. While many responses demonstrated satisfaction with present practices, a major proportion of respondents identified knowledge gaps and a need for methodological development (Fig. 1).

The remainder of the meeting focused on discussing best practices, metadata requirements, and main knowledge gaps within proxy-specific working groups: diatoms, dinoflagellate cysts, foraminifera, radiolaria, silicoflagellates, organic and stable-isotope geochemistry, highly branched isoprenoid lipids (HBIs), and sedimentary DNA. Throughout the workshop, answers to the question "What holds the most potential in our field?" were collected using an interactive vision board. The outcome from this exercise was discussed as a final activity of the workshop.

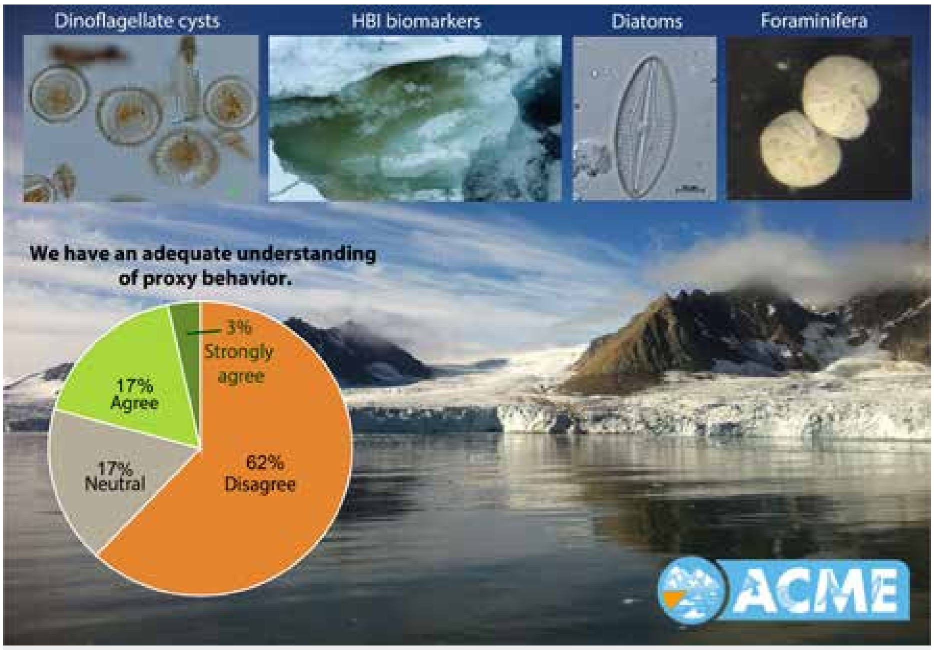

Figure 1: The first ACME workshop focused on improving our understanding and usage of Arctic paleoenvironmental proxies (image credit: Anna Pienkowski, Kaarina Weckström, and Maija Heikkilä).

Suggestions for "best practices" identified by each proxy group encompassed all steps from sampling design and sample collection, through sample handling and laboratory analyses, to data analysis and interpretation. While several recommendations were similar across groups (sampling design, collection), some proxy-specific recommendations were proposed regarding sample handling (storage conditions, processing prior to analysis); laboratory analyses (protocols, counting methods); and data interpretation (e.g. aspects affecting proxy formation, ecological knowledge). Based on the suggested best practices, groups drafted recommendations on the most important information to be included as metadata in the planned ACME database, or other openly available data repositories.

During the discussions, participants identified key proxy-specific knowledge gaps, including: microfossil species ecologies and taxonomy; microfossil and biomarker preservation; source- and environment-specific biomarker production; and limited reference libraries for sedimentary ancient DNA. One of the most important gaps indicated by the diatom and foraminifera groups was the lack of unified, openly available modern Arctic reference datasets. Open science/open data was highlighted as holding the most promise in the field. Proxy-specific groups brought forward the need for unified analytical protocols and laboratory intercalibration studies. Multidisciplinary collaboration and multiproxy approaches were emphasized. Advancing our ecological understanding, identifying tipping points in the Earth system, multidimensional reconstructions, unraveling biodiversity trends and ecosystem networks, and improving predictive models by proxy–data assimilation were listed among the items holding the most potential.

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doi.org/10.22498/pages.30.1.57

Unraveling the complex relationship between solid-Earth deformation and ice-sheet change

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PALSEA-SERCE joint workshop, online, 13-16 September 2021

Better understanding the ice-sheet and solid-Earth processes that drive paleo sea-level change remains an important topic discussed at the 2021 joint PALSEA-SERCE virtual meeting (PALSEA: PALeo constraints on SEA level rise, pastglobalchanges.org/palsea; SERCE: Solid Earth Response and influence on Cryospheric Evolution, scar.org/science/serce/serce). The meeting (pastglobalchanges.org/calendar/26991) spanned four half-days and included 29 talks, 24 posters, and several group discussions. Over 110 participants joined the meeting and engaged in written and live conversations.

Most presentations revolved around two main themes: (1) developing and improving numerical models investigating the interactions between ice-sheet dynamics and solid-Earth deformation; and (2) providing new observations on paleo sea levels, ice-sheet retreat, and ongoing Earth deformation. From the modeling perspective, an important theme was that climate- and boundary-condition uncertainties remain large, requiring a move towards large ensemble simulations and machine-learning approaches. Within the observational science, new data were presented on important locations across the globe including Greenland, Northern Europe, Micronesia, the Bahamas, Antarctica, and the USA. These new observations and careful compilations build the foundation for improving models of solid Earth deformation (glacial isostatic adjustment, GIA) and our understanding of past ice-sheet change.

In addition to paleo observations, speakers presented geodetic observations related to modern melt loss. One issue repeatedly mentioned was the uncertain future of geodetic observations from Antarctica, which are instrumental in understanding ice-mass loss and solid Earth structure. The Polenet stations (Fig. 1), supported to date by the US National Science Foundation, are at risk of being decommissioned in the near future. These geodetic observations are instrumental to this community, and a community effort to demonstrate the value of keeping these stations running, as well as a formulation of new science goals, is needed.

As the observations increasingly improve, models of GIA used to fit them, continue to evolve as well. GIA models often assume that solid-Earth structure (most importantly viscosity) only varies with depth, which allows for fast computations and the ability to thoroughly explore trade-offs and uncertainty.

Figure 1: Erik Kendrick (right) installing the GPS monument at Gould Knoll (GLDK) on Thurston Island in the Amundsen Sea. Jeff Amantea (left) looks towards the Twin Otter and broadband seismic station that is part of the POLENET/A-NET project (polenet.org) (photo credit: Terry Wilson).

While these models continue to have merit, more complex models are increasingly employed and possibly even required by the observational record. The computational cost of these models hinders data assimilation through large ensemble runs; however, adjoint techniques might provide a path forward to efficiently constrain 3D viscosity with sea-level data. In addition to lateral variability, several speakers explored the role of transient and nonlinear rheologies and demonstrated that these complexities are not only more realistic, but may also help reconcile sea-level observations on different timescales. An upcoming challenge in the community will be to efficiently constrain all the new parameters that emerge from these models ranging from grain-size and temperature, to water content and background stress. Tighter connections to the mineral physics and geodynamic community are critical in achieving this goal.

As GIA models evolve, we need to develop standards for benchmarking and output sharing. In the past, the PALSEA community has produced community papers surrounding data compilations (Düsterhus et al. 2016) and research priorities (Capron et al. 2019). A new community effort should tackle GIA modeling standards. This could include describing and unifying modeling options, and quantifying their importance, as well as identifying a baseline set of benchmarks to be used. Additional benchmarking is needed for components related to horizontal motion and 3D viscosity structure. A community effort should develop recommendations for code and output sharing, including standardized output formats.

We thank all the participants who engaged in this workshop and the supporting organizations: PAGES, the International Union for Quaternary Research (INQUA), the Scientific Committee on Antarctic Research (SCAR), and Columbia University.

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doi.org/10.22498/pages.30.1.58

An update on advances in paleoscience in the Carpathian-Balkan region

Marcel Mindrescu[1,2] and Ionela Grădinaru[2,3]

Carlibaba (Fluturica), Suceava County, Romania, 5-9 October 2021

Central Eastern Europe (CEE) and the Carpathian-Balkan region (CBR) are of particular interest for paleoscientific investigations for several reasons. Firstly, the location at the contact/transition between the smaller landmass of Western Europe, where the climate is largely dictated by North Atlantic air masses, and the large continental mass extending beyond the Carpathian range, which falls under the influence of excessive continental climate, turns the Carpathian and Balkan ranges into a boundary between the two major climatic influences of the European continent. Secondly, the significant elevation range peaking at 2925 m asl favors the capture of regional and continental-scale climatic signals and determines a strong vegetation gradient. Thirdly, the diversity of landforms—including those with glacial, periglacial, or paraglacial origins; underground cavities (caves and shafts; see Fig. 1); lakes; and peatbogs—provide opportunities for paleoclimate and paleoenvironment reconstructions.

Until recently (i.e. before the 2010s), CEE was unrepresented in large data reviews that discussed well-dated, high-resolution investigations of past climate and environmental conditions and studies on human impact on the local and regional environment. However, as new paleoclimatic records are continuously being generated, this area is no longer a blank spot in regional and continental-scale climate reconstructions. The significant advancement of paleoscientific research in this region is ascribed to recent scientific efforts, including five regionally relevant meetings focused on climate changes and paleoclimate reconstructions organized in the past decade in Romania with the continued support of PAGES, and the establishment of a dedicated working group, the Carpathian Climate and Environment Working Group CarpClim (pastglobalchanges.org/science/end-aff/carpclim).

The Carpathian-Balkan Paleoscience Workshop (CBPW) 2021 (pastglobalchanges.org/calendar/26996) was an initiative of the Geoconcept Association of Applied Geography (geoconcept.ro) supported by PAGES and endorsed by the Geography Department of the University of Suceava in Romania and other research and academic institutions and structures. The proceedings of the workshop were held in a traditional Bukovinian village located on a highland plateau (ca. 1250 m asl) in the Northern Romanian Carpathian as a "green scientific event" committed to respecting public health safety requirements and providing support for local communities, while maintaining a low carbon footprint.

CBPW 2021 was designed as an interdisciplinary and multidisciplinary scientific event focusing on novel investigations of climate and environmental changes in the CBR since the Last Glacial Maximum. The contributions approached a diverse range of topics which included, most notably: single and multi-proxy paleoclimate reconstructions based on peatbog and lacustrine sediment archives; reconstructions of characteristics and extents of glaciers and glacial landforms in the Carpathian and Balkan ranges; cave records as indicators of climate variability; vegetation history, past fire regimes and their drivers; dendrochronological investigations; assessments of past and present human impacts and pollution history; studies of geoarchaeology, geohistory and landscape archaeology; land use/landcover changes in relation to climate variability; and modeling techniques for climate and environmental variability. Additionally, CBPW 2021 included a session dedicated to sustainable forest management in the CBR in the context of adaptation to climate change and the necessity for continued provisioning of the forest ecosystem services communities depend upon, which included the topics of forest ecology, science, and management relating to global change (e.g. climate disruption, alteration of disturbance regimes, and increasing pressure for exploitable natural resources).

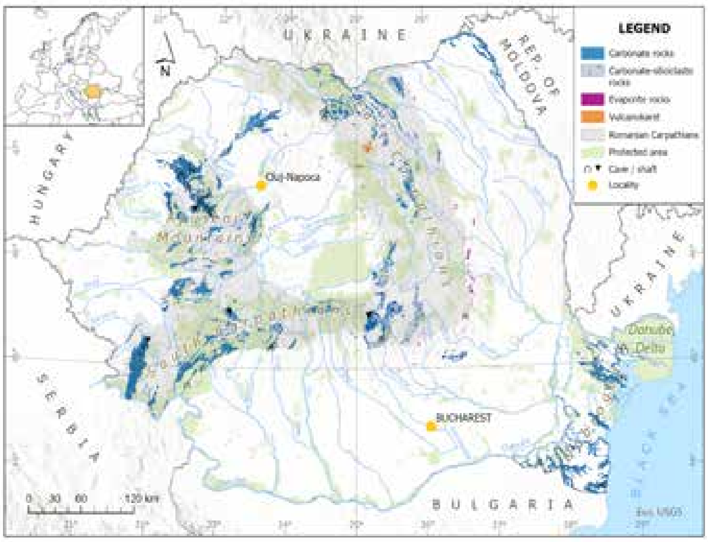

Figure 1: Karst lithology and caves in Romania (Bădescu and Tîrlă 2020). Information about 12,300 caves is archived at the "Emil Racoviță" Speleological Institute in Bucharest, of which only 6816 were included in a printed catalog of caves in Romania. Using data from various publications, 8128 caves are compiled in an online database at speologie.org (Onac and Goran 2019).

The workshop was attended by about 50 participants from Romania, Ukraine, the Republic of Moldova, Russia, Hungary, Bulgaria, Czech Republic, Poland, Germany, the Netherlands, Sweden, France, Italy, Spain, the United Kingdom, Ghana, the USA, Brazil, and Colombia. Both the variety of scientific approaches introduced by the researchers and the diversity of the participants in terms of scientific backgrounds and level of research experience (including early-career and senior researchers and academics) were noteworthy. Organizers were fully committed to ensuring that CBPW 2021 offered equitable opportunities for participation in terms of gender, ethnicity, and age to all scientists who were interested in attending.

In the current pandemic context, which has disrupted the social and networking aspects of scientific meetings worldwide, this hybrid event was able to provide a space for sharing knowledge and boosting collaboration for future research, as well as for yielding high quality scientific content suitable for publishing a special volume of a Web of Science journal dedicated to advancing paleoscience in the Carpathian-Balkan region.

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doi.org/10.22498/pages.30.1.59

PAIGE: Chronologies for Polar Paleoclimate Archives – Kickoff conference of a new Italian–German partnership project

Florian Adolphi[1], C. Barbante[2,3], P. Bohleber[3], G. Mollenhauer[1], T. Tesi[2] and F. Wilhelms[1]

Bologna and Venice, Italy, 6-8 October 2021

The new international collaborative project called PAIGE (Chronologies for Polar Paleoclimate Archives - Italian-German Partnership) is funded by the Helmholtz Association and aims to strengthen collaborative research between the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) and the Italian Institute of Polar Sciences of the National Research Council of Italy (ISP-CNR). The project's key theme revolves around the ambitious goal of linking chronologies for paleoclimate archives from ice cores and sediment cores.

At the beginning of the PAIGE project, an international workshop on chronology of high-latitude paleoclimate archives was held in Bologna and Venice, Italy, in October 2021. The aim of the conference was to identify the state of the art but also the main gaps of knowledge regarding chronologies and synchronization of polar paleoclimate archives. The conference was held in a hybrid format, allowing for in-person and online attendance. Participants included students and early-career researchers, as well as senior scientists. The plenary session featured 11 invited keynotes followed by discussion and a final wrap-up session each day.

During the conference, a common theme developed around the potential and limitations of linking chronologies from different archives as well as hemispheres. New approaches and techniques for achieving precise chronological control were presented. A special role in this context is played by identifying traces of volcanic eruptions through their chemical signature, as well as tephra deposits. On this topic, Michael Sigl (University of Bern, Switzerland) presented the potential of volcanic signals to improve ice-core dating during the Holocene, as well as to investigate the short-term climatic and societal impact of volcanic eruptions. His talk was complemented by Anders Svensson's (University of Copenhagen, Denmark) presentation on bi-polar ice-core synchronization by means of ice-core sulfate records over the last glacial period. Allessio Di Roberto (INGV, Pisa, Italy) then discussed how to bridge the gap to the marine sector by using tephra particles found in ice cores and sediments. Another powerful synchronization tool is cosmogenic radionuclides such as ^{10}Be; Raimund Muscheler (Lund University, Sweden) presented how ice-core ^{10}Be and ^{36}Cl records can be used to detect changes in the cosmic ray flux, while Martin Frank (GEOMAR, Germany) illustrated the potential and challenges of using ^{10}Be to date marine sediments.

Felix Ng (Sheffield University, UK) showed recent advances in the model treatment of impurity diffusion in ice cores, which is directly relevant to the interpretation not only of volcanic peaks, but also of cosmogenic radionuclides found at greater depths. In addition, Francesco Muschitiello (University of Cambridge, UK) elaborated how to use advanced probabilistic methods to synchronize environmental archives based on their proxy records. Besides synchronization, another focus was on the absolute dating of ice cores and sediments using radiometric methods. Florian Ritterbusch (University of Science and Technology of China) discussed recent advances in using radiogenic noble gas isotopes of Ar and Kr for absolute ice-core dating, with particular examples of how this novel dating technique by atom trace trap analysis can constrain existing chronologies. Walter Geibert (AWI, Germany) showed new approaches of using U-series isotopes to obtain high-resolution chronologies in marine sediments back to ~450 kyr ago. For younger sediments, radiocarbon is the most commonly employed dating method and Claire Waelbroeck (LSCE, France) and Jutta Wollenburg (AWI) discussed challenges related to the marine reservoir age and post-depositional alterations of carbonate shells, respectively.

Inspired by two days of presentations and discussions, the third day of the workshop was dedicated to ongoing work within PAIGE: in Bologna, early-career researchers working on permafrost dynamics presented and discussed their results and explored options for increased collaboration and exchange between the institutes. In Venice, a subgroup intensified the discussion on obtaining high-resolution impurity data from ice cores, specifically with laser ablation inductively-coupled plasma mass spectrometry (LA-ICPMS).

Ultimately, the outcome of the workshop highlighted not only the importance of linking chronologies from marine and ice archives, but also the ambitious nature of such an endeavor. No single dating method is likely to deliver this breakthrough, but the path forward lies in a multi-disciplinary combination of high-resolution stratigraphic dating methods in concert with absolute age constraints from radiometric techniques. Accordingly, it will be crucial to have marine and ice-core experts continue and intensify their inter-disciplinary dialogue. Facilitating this exchange will be a lasting added value of the PAIGE project to the two scientific communities. People interested in learning more about the project and upcoming activities are invited to contact Florian.Adolphi@awi.de or Pascal.Bohleber@unive.it.

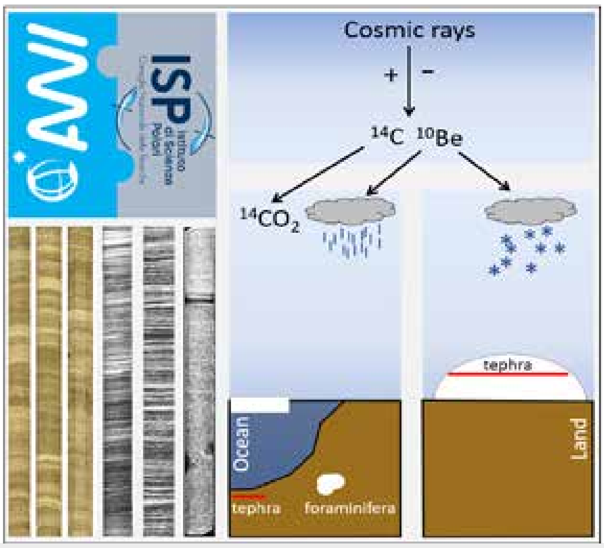

Figure 1: Schematic illustration of the PAIGE's goals to connect the chronologies of ice-cores and marine sediments as well as AWI and ISP-CNR in order to improve our understanding of past climate changes and enhance scientific exchange between communities.

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doi.org/10.22498/pages.30.1.60

C-PEAT at COP26

Julie Loisel[1] and Angela Gallego-Sala[2]

United Nations Climate Change Conference (COP26), Glasgow, Scotland, 31 October - 12 November 2021

On Friday, 5 November 2021, the C-PEAT working group, in collaboration with PAGES and Future Earth, presented an exhibit during the 26th United Nations Climate Change Conference (COP26) in Glasgow, Scotland. Professors Julie Loisel and Angela Gallego-Sala (the group co-leads) gave the lecture "Getting to know peatlands, the largest natural land carbon stores on Earth", presenting updated knowledge on the global peatland carbon stocks, peatlands' sensitivity to past and future climate change, and the role of peatlands as natural climate solutions.

Peatland Pavilion

The C-PEAT lecture was hosted by the Peatland Pavilion (wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/37197/COP26GP.pdf) that was organized by UNEP's Global Peatlands Initiative. The Pavilion's exhibit hall was packed with art pieces and artefacts from peatlands. The agenda was fully booked with panels and lectures for the entirety of the two-week conference. At the Pavilion, scientists and practitioners drew attention to the importance of peatlands in climate change mitigation, mainly via peatland restoration and protection. That peatlands are considered important enough to be granted a Pavilion at a COP meeting speaks volumes in itself. Their role as global cooling agents is now widely accepted; likewise, the threats these natural carbon sinks face from climate and land-use changes are also well known. Protecting peatlands has been described as "one of the most important tasks of this decade".

C-PEAT contributions

The C-PEAT group contributed an interactive peatland map (julieloisel.com/cpeat) that showcases > 75 sites from 20 countries that have been studied by the C-PEAT scientific community. The map was combined with a library of peat cores that were displayed at the Peatland Pavilion. This part of the exhibit helped attendees–both online and in-person–to appreciate where peatlands are located and what peat looks like. The map was created by Sedrick Utt, an undergraduate student researcher in the Department of Geography at Texas A&M University, USA; his work was funded by PAGES.

In collaboration with Patrick Campbell, who is an artist and peatland enthusiast, we also presented six drawings of peatland landscapes (Fig. 1), each representing a different stage in a peatland's development. For each portrait, different proxies were also drawn to represent the role of peatlands as natural archives; short texts explained how paleoecologists can reconstruct past environments and infer past landscapes from said proxies.

Figure 1: Artistic rendition of a peatland landscape throughout its development. These six posters were presented as part of the Peatland Pavilion exhibit at COP26. Drawings by Patrick Campbell. High-resolution images available for download at julieloisel.com/cpeat.

The talk (youtube.com/watch?v=Q4vRIefClZc) was aimed at a broad audience of informed stakeholders, practitioners, and scientists. Topics covered included: "How do we quantify the global peatland carbon stock?", "How does climate affect the peatland carbon sink?", "How will peatland extent change with warming?", and "Future research directions for C-PEAT". A PDF version of the slideshow is available (drive.google.com/file/d/1HnLJAwmJ9G3f-ImlGhC5FCXM_fwCqW4o/view); everyone is welcome to use the slides.

Achievements and concluding remarks

The Peatland Pavilion provided clear messages about the importance of restoring degraded peatlands–namely through rewetting–and protecting pristine ones. The work of peatlands as natural solutions to mitigate climate change sits well within COP26's "Glasgow Leaders' Declaration on Forests and Land Use", which was signed by more than 140 countries promising to work collectively to halt and reverse forest loss and land degradation by 2030. This pledge should be beneficial for peatlands; our interpretation is that the commitment will encompass efforts to help halt the further degradation of peatlands worldwide. In addition, countries such as Chile, Peru, Indonesia, and the DRC included peatlands in their national pledges under the Paris Agreement–known as Nationally Determined Contributions (NDCs)–for the first time. Lastly, multilateral development banks (MDBs) now consider both the extraction of peat and electricity generation from peat to be universally not aligned with the Paris goals. This is important because it may change how investments are made in terms of what is considered sustainable development, which should include the avoided conversion of peatlands.

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doi.org/10.22498/pages.30.1.61

Land-cover and land-use change through the Holocene: Wrapping up the PAGES LandCover6k working group

Austin "Chad" Hill[1], N. Whitehouse[2], M. Madella[3], K.D. Morrison[1] and M.-J. Gaillard[4]

Online, 2 - 4 December 2021

The PAGES LandCover6k working group (Gaillard et al. 2015; pastglobalchanges.org/landcover6k) met in December 2021, via Zoom, for the final scheduled conference on the progress of the group (pastglobalchanges.org/calendar/26936). Thirty-six authors presented 29 papers, over four sessions, on regional reconstructions of land cover and land use, as well as the related topics of synthesizing and publishing the output of the project and collaborating with climate modelers. The meeting, originally planned to be held in person in Philadelphia in 2020, was moved online due to ongoing Covid concerns. While it was disappointing not to be able to host our colleagues in-person, the online format allowed many people to present, and a wider audience to attend, than might have been possible otherwise.

Global overview and regional progress

A global overview of the progress made during the working group's lifetime was provided by Marie-José Gaillard, Kathy Morrison, Marco Madella, and Nicki Whitehouse. Significant headway has been made with the publication of both land-cover and land-use reconstructions (e.g. Gaillard et al. 2018, Morrison et al. 2021, Githumbi et al. 2022) for the Holocene. These reconstructions are designed to help improve Anthropogenic Land-Cover Change (ALCC) scenarios such as HYDE 3.2 and achieve paleoclimate model simulation experiments (e.g. Strandberg et al. 2022). Four sessions were divided by global region, providing regional subgroups with the opportunity to provide updates on the progress of past land-use and land-cover change mapping. In a few regions, including Europe, China, and the Near East, data analysis is nearly complete for both pollen-based reconstructions of past land cover and archaeological data-based land-use maps. In many other regions, work has progressed further for either land cover or land use. For land-use reconstructions, much of the discussion revolved around the different approaches that have developed for different regions, especially methods of interpolating archaeological site data to the regional scale, based on the differences in the availability of published site data and accurate ^{14}C dates.

Integrating land cover and land use

Two key recurring topics discussed throughout the conference were the challenge of incorporating regional land-use data into a final global database so that it can be useful to climate modelers, and the challenge of integrating land-use and land-cover data. One important ongoing effort to do this comes in the form of a recently awarded PAGES data stewardship scholarship. This will help fund the long-term curation of pollen-based REVEALS land-cover reconstructions, gridded at 1° x 1° over 25 time windows throughout the Holocene (e.g. Githumbi et al. 2022), a new global historical Per Capita Land-Use (PCLU) database, and regional historic land-use data using the LandCover6k classification system gridded at 8km x 8km (Morrison et al. 2021). The REVEALS reconstructions for Europe, first (Trondman et al. 2015; Marquer et al. 2014) and second (Githumbi et al. 2022) generations, are already archived in PANGAEA (Gaillard 2019; Marquer et al. 2019, and Fyfe et al. 2021), as well as the land-use map for the Middle-East at 6 kyr BP (Hammer 2020).

The future of LandCover6k

This was the final conference of the PAGES LandCover6k working group in its current incarnation. However, a lively thread running through the meeting was the ongoing nature of the work, and the need for the work to continue. Discussions continue about how to finish individual publications, how collaborations between land-use and land-cover researchers will endure, and how the results from regional land-use work will be brought together into the final global database, as well as new research directions.

One important change, as LandCover6k transitions to the next stage, will be in leadership. Marie-José Gaillard has recently retired and will step down as group coordinator for future iterations of the project. We thank Marie-José for her tireless work inspiring, organizing, and shepherding the group over the last seven years. We also wish to thank all colleagues worldwide who coordinated subgroups, provided and/or collected data, contributed to land-use and land-cover reconstructions, and worked on the publication of datasets and results. Last but not least, we are grateful to all members of the core group (Victor Brovkin, Jane Bunting, Anne Dallmeyer, Erle Ellis, Jed Kaplan, Kees Klein Goldewijk, Sandy Harrison, Boris Vannière, and Peter Verburg) and the rest of the coordinating group, in addition to the authors (Jennifer Bates, Oliver Boles, Andria Dawson, Esther Githumbi, Emily Hammer, Sandy Harrison, Furong Li, Stefania Merlo, and Marc Vander Linden) for the valuable discussions and exchanges of ideas during numerous meetings over the years.

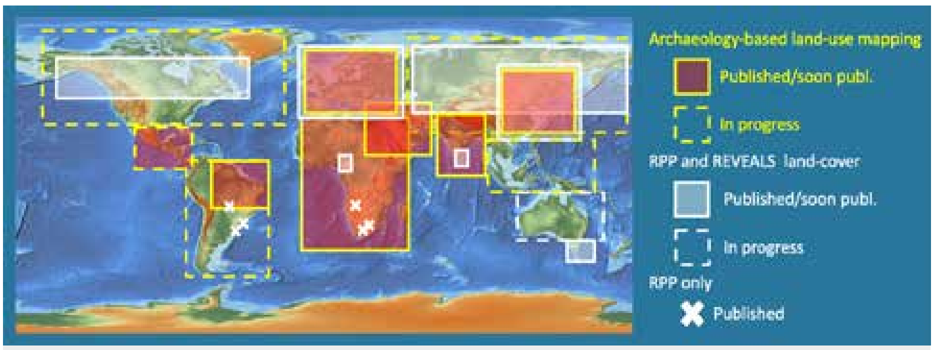

Figure 1: Progress of PAGES LandCover6k publications by region (image credit: K.D. Morrison, M.-J. Gaillard).

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doi.org/10.22498/pages.30.1.62

Data stewardship projects underway

Darrell S. Kaufman

Eleven new PAGES-funded Data Stewards are helping PAGES working groups to discover, analyze, and curate community data resources.

Professional scientific organizations are playing an increasingly important role in motivating the cultural shift toward FAIR (Findable, Accessible, Interoperable, and Reusable) data practices (PAGES Scientific Steering Committee 2018). PAGES now offers its working groups financial support to help develop open data resources that facilitate high-impact global change research. The first nine PAGES Data Steward Scholarships are now underway. Stipends averaging USD 14,400, and ranging up to USD 20,000, recognize and reward early-career researchers and established specialists for their valued efforts to compile and curate data products for the long-term benefit of the global paleoscience community.

These data stewards are serving key roles in the life cycle of PAGES working groups, both in the data-discovery and data-reporting stages (Fig. 1). They are helping to accelerate the rate at which past-global-change data are entering the public domain. They are gathering the essential metadata needed for intelligent data reuse, and are formatting the datasets so they are amenable to analysis by open-source code. PAGES data stewards are implementing practices that model and promote FAIR data principles (Wilkinson et al. 2016), while making use of, and reducing loss of, valuable data (Kaufman and PAGES 2k special-issue editorial team 2018). Their contribution as curators of community data resources will extend well beyond the lifetime of a working group (Williams et al. 2018).

PAGES-funded data stewards are helping PAGES working groups to achieve their goals in a variety of ways. Specifically:

C-PEAT (Carbon in Peat on Earth through Time) held a series of "data-collection happy hours" to gather contributions of peat-based proxy records from around the world. The data and essential metadata are being standardized for use in ecosystem models to understand carbon and water cycling.
pastglobalchanges.org/c-peat/data

C-SIDE (Cycles of Sea-Ice Dynamics in the Earth system) has compiled a dataset of sea-ice records from the Southern Ocean over the last glacial-interglacial cycle and is preparing a data descriptor for publication.
pastglobalchanges.org/c-side/data

OC3 (Ocean Circulation and Carbon Cycling) is building on its World Atlas of late Quaternary foraminiferal oxygen and carbon isotopes by generating quality-controlled age models for the highest resolution records, with the goal of resolving rapid changes during the last deglacial transition.
pastglobalchanges.org/oc3/data

2k Network is assembling all existing 2k datasets, including those featuring paleo temperature, moisture and isotopic records of the Common Era, to improve their accessibility and interoperability. They plan to develop a one-stop portal that describes the datasets in multiple languages. Within the 2k Network, **CoralHydro2k** has added 41 seawater oxygen-isotope records to its data compilation. Nearly half of these were previously "hidden" behind paywalls and in grey literature. These data will help calibrate marine carbonate proxies and improve models of ocean-atmosphere interactions. **CLIVASH2k**'s community-wide data call netted 110 new sodium and sulphate datasets from Antarctic ice cores. The data were received in various forms and are being compiled into a uniform format, while fleshing out missing metadata. The data will be used to reconstruct Antarctic atmospheric circulation and surface mass balance over the past 2000 years.
pastglobalchanges.org/2k/data

PALSEA (PALeo constraints on SEA level rise) is merging the recently published Holocene sea-level database with the existing world atlas of last interglacial sea-level indicators. The group is planning to improve the online database interface to help address questions about the drivers of sea-level change at local to global scales.
pastglobalchanges.org/palsea/data

PEOPLE 3000 (PalEOclimate and PeopLing of the Earth) is expanding its global compilation of archaeological radiocarbon data to support research on human paleodemography.
pastglobalchanges.org/people-3000/data

SISAL (Speleothem Isotope Synthesis and AnaLysis) is updating its well-established database to include speleothem trace-element time series. It plans to develop a computer app to enhance database accessibility. pastglobalchanges.org/sisal/data

Any member of a PAGES working group can apply for a Data Steward Scholarship. Contact your working group leaders. For more information see the PAGES website: pastglobalchanges.org/dss

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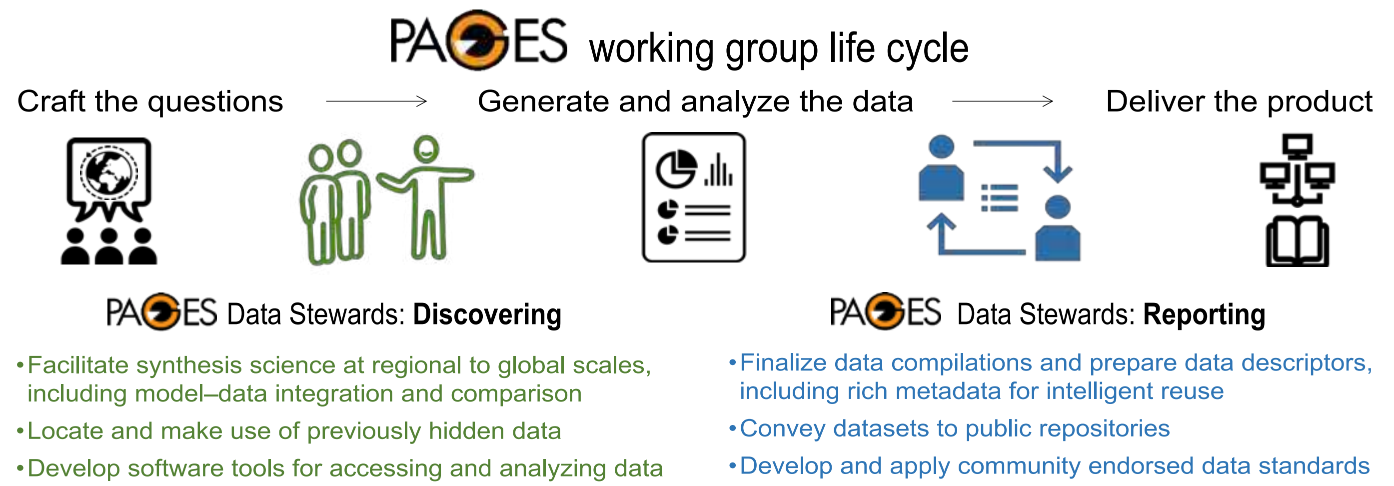

Figure 1: Data stewards are supported financially by PAGES to serve key roles in the life cycle of PAGES working groups, both in the data-discovery and data-reporting stages.

doi.org/10.22498/pages.30.1.63

What can APIs do for you?

Wendy Gross[1], C. Morrill[1], E. Gille[1,2] and E. Shepherd[1,3]

As the spatial and temporal resolution of scientific datasets and the culture of data sharing grow, more data on past global changes are now available than ever before. Efficiently discovering, downloading, and integrating data into analyses is critical for making full use of this surge of information. Researchers have long used Graphical User Interfaces[1], or GUIs, to manually search and download data, but Application Programming Interfaces, or APIs, can handle these tasks in a more automated fashion. In fact, APIs are the behind-the-scenes conduit for many different types of information we use every day, from weather forecasts within smartphone apps to flight schedules aggregated on travel websites.

APIs are the technological backbone that let two computer programs communicate over the internet. Each API defines a set of rules that specify the parameters by which requests (or "calls") can be made, as well as the format of the computer-readable information that is provided in response. World Data System repositories such as the World Data Service for Paleoclimatology (WDS-Paleo)[2], PANGAEA[3], and Neotoma[4] provide APIs, as do other data and information sources such as publishers (e.g. Springer, Wiley), publication databases (e.g. CrossRef, Web of Science), domain-specific databases (e.g. Global Biodiversity Information Facility), and analysis tools (e.g. ArcGIS).

A request to an API is usually written in the form of a specially-formatted web address, or Uniform Resource Locator (URL). Scientists can call an API by simply entering such a URL into their web browser or by incorporating calls to an API in data analysis code. These new capabilities open more automated ways of first finding and accessing information, and then integrating information, both from different sources, and with different analysis tools.

The ability to discover and download information programmatically via an API, as opposed to manually through a GUI, increases efficiency and diminishes the possibility for human error. For example, APIs make it easier to repeat a search (perhaps to find newly archived datasets or updates to existing datasets) or to gather information quickly for initial data exploration (perhaps to identify certain geographical areas or parameter types with sufficient amounts of data for an analysis). APIs can also make it more efficient to search multiple data providers. While requests must be structured to match the requirements of a specific API, they can be a useful way to locate data across several repositories. In fact, the federated data search provided by the WDS-Paleo API uses the Neotoma API to retrieve information about datasets.

API requests can be integrated with many programming languages (e.g. Python, R, MatLab), effectively creating a pipeline of data to tools for analysis. For example, functionality to access data from the PANGAEA, and Neotoma data repositories via their APIs exists in some Python[5] and R[6,7] packages (e.g. Goring et al. 2015) and the WDS-Paleo also provides example API requests in these languages[8]. Incorporating API requests into a scientific workflow promotes reproducibility and repeatability of research. Encoding all steps of the workflow from data discovery and download to processing and analysis provides complete documentation of the research methods, including the criteria used to select datasets. Some APIs also perform analysis directly: for example in the geospatial ecosystem, ArcGIS APIs[9] and Open Geospatial Consortium APIs[10] perform geospatial analysis, including image analysis and feature classification.

While APIs provide the ability to access formatted information directly from computer systems of authoritative sources, thereby streamlining data access and analysis, there are still some obstacles to integrating data from different repositories or sources seamlessly (e.g. EarthLife Consortium API[11]; Uhen et al. 2021). For example, interoperability and reusability of paleoenvironmental data also require enhanced common standards and workflows for metadata and data reporting (Bothe et al. 2021; Khider et al. 2019; Morrill et al. 2021; Williams et al. 2018). These improvements, in concert with technological advances such as APIs, will accelerate discovery from the many decades of data collection by the paleo community.

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Uhen MD et al. (2021) Front Biogeogr 13: e50711
Williams J et al. (2018) PAGES Mag 26: 50-51

LINKS

[1]For example: ncei.noaa.gov/access/paleo-search, pangaea.de, apps.neotomadb.org/explorer
[2]ncei.noaa.gov/access/paleo-search/api
[3]ws.pangaea.de
[4]api.neotomadb.org/api-docs
[5]github.com/pangaea-data-publisher/pangaeapy
[6]docs.ropensci.org/pangaear
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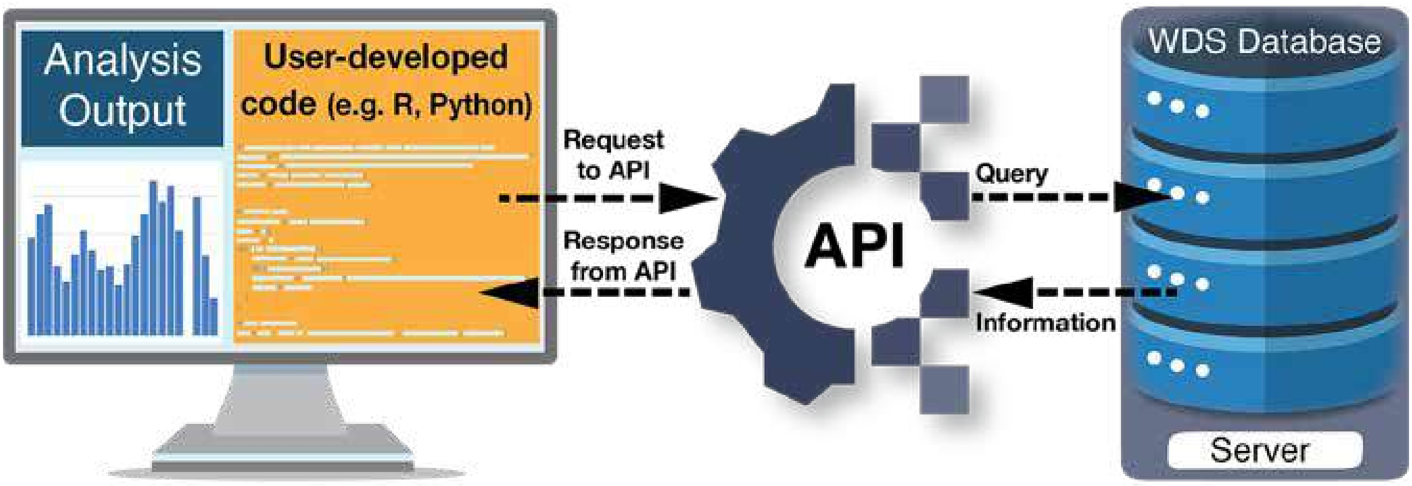

Figure 1: Example workflow for programmatically using a World Data Service (WDS; e.g. WDS-Paleo, PANGAEA, Neotoma) API. Starting with user-developed code (yellow box), information from a data provider is discovered and accessed via the API, and then incorporated into a scientific analysis. See the WDS-Paleo API Tutorial[8] for sample code in R and Python.

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Design
sujata design

Parent program
PAGES is a Global Research Project of Future Earth.

Supporters
The PAGES International Project Office and its publications are supported by the Swiss Academy of Sciences (SCNAT) and the Chinese Academy of Sciences (CAS).

Printed on recycled paper by
Läderach AG
Bern, Switzerland

Hardcopy circulation 2150

ISSN 2411-605X / 2411-9180

doi.org/10.22498/pages.30.1