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Coupled insights from the palaeoenvironmental, historical and archaeological archives to support social-ecological resilience and the sustainable development goals

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Abstract

Many governments and organisations are currently aligning many aspects of their policies and practices to the sustainable development goals (SDGs). Achieving the SDGs should increase social-ecological resilience to shocks like climate change and its impacts. Here, we consider the relationship amongst the three elements—the SDGs, social-ecological resilience and climate change—as a positive feedback loop. We argue that long-term memory encoded in historical, archaeological and related 'palaeo-data' is central to understanding each of these elements of the feedback loop, especially when long-term fluctuations are inherent in social-ecological systems and their responses to abrupt change. Yet, there is scant reference to the valuable contribution that can be made by these data from the past in the SDGs or their targets and indicators. The historical and archaeological records emphasise the importance of some key themes running through the SDGs including how diversity, inclusion, learning and innovation can reduce vulnerability to abrupt change, and the role of connectivity. Using paleo-data, we demonstrate how changes in the extent of water-related ecosystems as measured by indicator 6.6.1 may simply be related to natural hydroclimate variability, rather than reflecting actual progress towards Target 6.6. This highlights issues associated with using SDG indicator baselines predicated on short-term and very recent data only. Within the context of the contributions from long-term data to inform the positive feedback loop, we ask whether our current inability to substantively combat anthropogenic climate change threatens achieving both the SDGS and enhanced resilience to climate change itself. We argue that long-term records are central to understanding how and what will improve resilience and enhance our ability to both mitigate and adapt to climate change. However, for uptake of these data to occur, improved understanding of their quality and potential by policymakers and managers is required.

1. Introduction

Projected increases in the frequency and/or intensity of climate-related extremes and the imminent threat of abrupt changes and tipping points (Cai *et al* 2016, Steffen *et al* 2018, Lenton *et al* 2019, Brovkin *et al* 2021, IPCC 2021) increase the exigency of understanding the nature of social-ecological resilience to past change. Tipping points represent an irreversible shift from one climate regime to another, and, along with climate extremes and generally abrupt climate change (but not necessarily tipping points), their occurrence will have highly significant implications for adaptive resilience of social-ecological systems (for definitions, see table 1). Adaptive resilience refers to the ability of a system to return to a similar but not identical state to the previous one; an ability to absorb shocks while maintaining function (Folke *et al* 2004, Walker *et al* 2004, Peregrine 2021). The 2030 Agenda for Sustainable Development program of action can be viewed as a response to issues impeding progress towards improved resilience. Essentially, it aims to facilitate transformations required to enhance sustainability and implicitly, adaptive resilience (Andrijevic *et al* 2020), through critical transformations (Sachs *et al* 2019).

As part of the 2030 Agenda, the sustainable development goals (SDGs) comprise 17 non-legally binding goals (United Nations 2015a) consisting of 169 targets that are assessed against pre-specified indicators. These goals are a mixture of 'planetary' (SDGs 6, 13–15) and 'social' (SDGs 1–12, 16–17) goals. By design, the goals overlap so as to provide seamless coverage of the key issues facing humanity and the environment. For example, Target 1.5, 11.b and 13.1 cover the remit of climatic and other natural hazards under different guises, Goal 1—Poverty alleviation, Goal 11—Safe cities and Goal 13—Combating climate change. Closely related to the Intergovernmental Panel on Climate Change reports (IPCC 2021, 2022), SDG13 specifically pinpoints the need for urgent action to combat climate change and its long-term effects and those of climate-related hazards. It also recognises the need for widespread implementation of the Sendai Framework for Disaster Risk Reduction (United Nations 2015b). Many international conventions, treaties and agreements are aligned with the SDGs (e.g. the Ramsar Convention, www.ramsar.org/).

Ostensibly, achieving the SDGs should improve social-ecological resilience to both abrupt climate changes and the persistent and growing impacts of anthropogenically-induced climate change. However, the impacts of the COVID-19 shock on progress towards the SDGs demonstrates the complexity of interrelationships, conflict even, amongst the goals. While the pandemic has had negative impacts on progress towards social SDGs, planetary health temporarily improved (United Nations 2020) before a rapid return to deteriorating planetary health as economies re-opened (Sachs *et al* 2021). This raises fundamental questions about the robustness of the SDG framework for improving resilience to anthropogenic climate change (Skene 2021). The fact that taking urgent action to combat climate change (SDG13) presents major challenges to 35 of the 37 OECD countries (Sachs *et al* 2021) adds to this concern. The interaction amongst SDGs, social-ecological resilience and climate change and its impacts, can be represented as a positive feedback loop (figure 1) in which the direction of flow is mediated by social and political structures and organisation.

Historical, archaeological and palaeoenvironmental data are pivotal to scholarship on the history of climate and society (Guillet *et al* 2017, Degroot *et al* 2021). As the only natural laboratory we have, they provide critical insight into responses of the physical environment, social and political organisation, religious practices, diet and agricultural practices to complex and abrupt change (figure 1). We argue that these long-term records can make a central contribution to understanding, and developing measures of, resilience and progress towards resilience (Berkes *et al* 2000, Folke *et al* 2002, Gómez-Baggethun *et al* 2013, Weiberg and Finnè 2018, Petzold *et al* 2020). Insights from these records should help shape policy approaches to implementing the SDGs, not least because local, regional and national framings of climate change impacts are commonly constructed in light of historical precedents (e.g. the fall of the Roman Empire). A more specific level of utility is the contribution long-term memory can have to developing, or understanding what constitutes, appropriate indicators and baselines for the SDGs (figure 1). This is especially relevant because while the SDGs may be considered multi-decadal in their outlook, the dynamics of physical and social systems are underpinned by 'slow variables' such as, for example, soil health, the education or health system, or water quality. Further, understanding the likely reactions of these slow variables to interventions, or 'fast variables' (Walker *et al* 2012), also requires information that extends beyond recent decades. It is therefore not possible to build resilience to change, or to adequately identify where thresholds for tipping points exist if these slow variables are not well understood (Folke *et al* 2010).

Reference to, or integration of, palaeoenvironmental, archaeological or historical records in the formulation of the SDGs or their indicators, however, is currently lacking. Collectively, these records provide warnings of the social-ecological costs of, and stories of long-term social-ecological resilience to, past abrupt change. This long-term data provides policy-relevant information to all three vertices of the feedback loop (figure 1) and their lack of consideration highlights the need to demonstrate how and why they deserve serious consideration by

Table 1. Working definitions of terms used in this manuscript. Note that there are a number of different versions of resilience (Walker *et al* 2004, Folke 2006, Folke *et al* 2010, Cote and Nightingale 2012, Wilson *et al* 2013, Fedele *et al* 2019).

Term	Description
Tipping point	The passing of a threshold at which small changes can lead to nonlinear change processes driven by internal system dynamics and that lead to a different system state. These changes can, but do not always occur much faster than changes in the relevant forcing (Williams *et al* 2011, Brovkin *et al* 2021). Realisation of impacts may take time (Dearing *et al* 2015, Kopp *et al* 2016).
Adaptive resilience	The ability of a system to return to a similar but not identical state to the previous one; an ability to absorb shocks while maintaining function (Walker *et al* 2004).
Social-ecological system	An open and interdependent system that encompasses climate, the biophysical and human interactions (see Folke *et al* 2004, Colding and Barthel 2019).
Abrupt change	An abrupt change can be associated with what Williams *et al* (2011) define as factors external to the system, or a result of non-linear responses to, for example, climate change. Changes due to factors internal to the system will typically be locally/regionally heterogeneous (Williams *et al* 2011). Abrupt change may occur over longer (e.g. multi-decadal- centennial) or shorter (annual—decadal) time scales. It may also occur as a result of nested processes or press and pulse pressures (Harris *et al* 2018) that may be largely due to internal or a mixture of external and internal factors.
Slow variables	Slow changing variables (relative to fast variables) within a system (Walker *et al* 2012). Generally controlled by external drivers, but also by intrinsic drivers.
Fast variables	These types of variables control the dynamics of a system (Walker *et al* 2012).
Vulnerability	Predisposition to be adversely affected by a change, includes sensitivity/susceptibility to harm and lack of capacity to adapt (IPCC 2022).
Exposure	Livelihoods, species, ecosystem, environmental function, service and resources, infrastructure or economic/social/cultural assets that could be adversely affected by change (IPCC 2022).

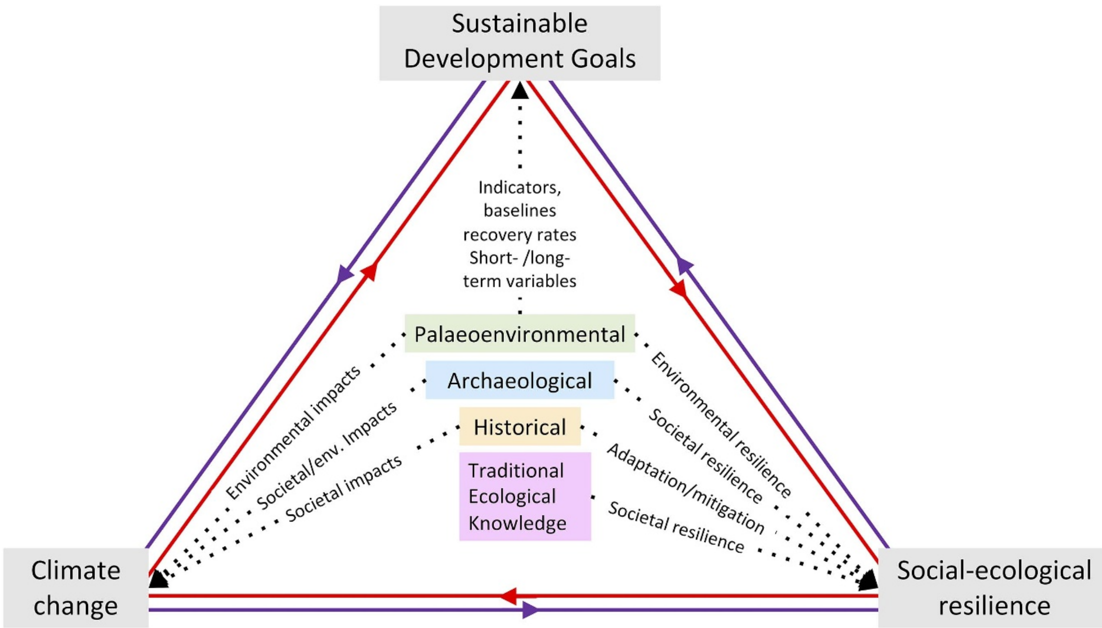

Figure 1. Simplified positive feedback loop between the sustainable development goals framework, social-ecological resilience and climate change. Contributions of historical, archaeological and paleo-data are central to understanding past environmental change, including responses to climate change and social-ecological resilience. Palaeo-data can also provide input into developing suitable indicators for some targets. If proceeding in a clockwise direction (red line), achieving the SDGs should enhance social-ecological resilience which then supports action on climate change and limitation of warming which then enhances the ability to achieve the SDGs. However, an anticlockwise (purple line) direction indicates that progress towards the SDGs falters which then negatively impacts on social-ecological resilience and impairs the ability to limit anthropogenic climate change. Escalating changes and reaching tipping points further undermines the ability to achieve the SDGs.

policy makers and managers. The need for long-term information is particularly acute if the resulting prognoses look beyond the most commonly modelled horizon of 2100 (Lyon *et al* 2021), now merely a single human lifetime away (Thiery *et al* 2021).

1.1. Towards resilience of physical environments: understanding the context of extremes and measuring long term variability and change

Palaeo-data has been extensively used to explore a variety of environmental changes (figure 1; table 2; Mills and Jones 2021), providing regional and global scale information about abrupt change due to both external forcing and non-linear responses to climate change (Williams *et al* 2011). Investigated changes include natural and anthropogenic vegetational changes (Ruddiman 2003, Kaplan *et al* 2010, Stephens *et al* 2019, Ellis *et al* 2021), temperature (e.g. PAGES2k Consortium 2012), hydroclimate (e.g. Steiger *et al* 2018), ocean acidification (Hönisch *et al* 2012), first human impacts on fresh surface water resources (Dubois *et al* 2018), groundwater variability (Gouramanis *et al* 2010), disturbance including fire (Mooney *et al* 2011, Codding *et al* 2014, Bliege Bird and Bird 2021), changes in pH and eutrophication (Smol *et al* 2001a), salinity (Smol *et al* 2001b), agricultural initiation and diversification (Barthel *et al* 2013, Guttmann-Bond 2010), human colonisation and settlement (Rolett and Diamond 2004, Seara *et al* 2020), greenhouse gas emissions (Masson-Delmotte *et al* 2013; indicators 9.4.1 and 13.2.2; table 3) and elemental and particulate contamination (Rose 2015, Chen *et al* 2016, 2020). These types of environmental changes have affected ancient societies such as the Khmer in Cambodia, the Akkadians in Mesopotamia and lowland Maya of southern Mexico and northern Central America (Weiss *et al* 1993, Hodell *et al* 1995, Buckley *et al* 2010). Although not referenced in relation to the SDG indicators, palaeo-information has already proven useful in water resources management and scenario planning (Smith *et al* 2007, Phillips *et al* 2009, Gurrapu *et al* 2022), stakeholder inclusion (Kerr *et al* 2022) or in improving risk or uncertainty estimates around extreme events (Lam *et al* 2017).

Importantly, placing recent extreme events described as 'unprecedented' over documented historical timeframes, like for example, the 2004 Indian Ocean Tsunami (Janakew *et al* 2008) or the southwestern North American megadrought (Williams *et al* 2022), into a long-term context is crucial for improving analyses of recurrence and/or frequency, magnitude (e.g. Klinger *et al* 2011, Lam *et al* 2017, Wilhelm *et al* 2019, Allen *et al* 2020). It is also useful for better understanding modes of environmental or social recovery and adaptative resilience (Wingard *et al* 2017). In this context, palaeo-data also provides the baseline canvas against which to evaluate the degree to which increasing human modifications of the environment have exacerbated hazards and, specifically, their contribution to hazard cascades (e.g. the 2018 Palu Earthquake; Bradley *et al* 2019).

Operationally, the SDGs rely on a variety of indicators against which to measure progress. Defining appropriate baselines for these indicators can be difficult, with many indicators relying on short-term baselines firmly rooted in the most recent decades. This means they may be premised on fundamentally flawed assumptions that a short and recent period sufficiently represents 'average' conditions. For example, Target 6.6 ('By 2020, protect and restore water-related ecosystems') relies on a 2000–2004 baseline to evaluate Indicator 6.6.1, 'Change in the extent of water-related ecosystems over time', and a 2016–18 baseline to specifically assess the extent of inland wetlands (www.unstats.un.org/sdgs/metadata/files/Metadata-06-06-01a). Target 6.6 is far from being achieved at the global or national levels (Convention on Wetlands 2021, van Denter 2021).

We use these indicators to discuss a number of issues associated with a baseline grounded in short-term data.

To do this, we selected ten areas hosting Ramsar-listed wetlands (www.ramsar.org/) and extracted the average reconstructed hydroclimate data (self-calibrating Palmer Drought Severity Index; scPDSI) from tree-ring based drought atlases (Cook *et al* 2007, 2010, 2016, Palmer *et al* 2015, Stahle *et al* 2016) for a $3^\circ \times 3^\circ$ area around each wetland. For each area we then generated a probability distribution based on 10 000 five year (for the 2000–2004 baseline) and three year (for the 2016–18 baseline) bootstrapped means drawn from the 605 years in common across all drought atlases (1400–2005 CE). For each area, average values for 2000–2004 and 2016–18 were compared with their respective probability distributions to see how unusual conditions for the 2000–2004 and 2016–18 periods were (figure 2).

This comparison highlights two key points. Firstly, if it can be assumed that 'average conditions' are optimal, these baseline periods are not optimal in many locations (figure 2; Higgs *et al* 2014, Falk *et al* 2019). Both periods were very dry for western Mexico, western Tajikistan and eastern Australia. Therefore, on the basis of these baselines, apparent progress (expansion) may occur simply due to the natural occurrence of wetter conditions regardless of any management interventions. Conversely, choosing an abnormally wet a baseline period can lead to conclusions that declines have occurred when in fact a return to drier conditions is simply part of natural variability rather than associated with any management intervention. For eastern Mexico, southern Vietnam, southern New Zealand, eastern China and southern Scandinavia, relative conditions during the two periods differed greatly. These five cases illustrate how high levels of interannual variability, and /or significant influence of multi-decadal climate oscillations—such as in Australia (Power *et al* 1999, Peel *et al* 2004)—make it more likely that a five- or three year period will fail to reflect average values. Only for southern Spain were approximately average conditions experienced in both baseline periods in the context of 605 years of data (figure 2). Various

Table 2. General description of archives and proxy types used to study environmental (particularly climate) variability. Typical resolution, temporal coverage and climate variables captured by archives are included and some key references for each archive type are provided.

		Proxies available	Resolution	Time Period (years)	Climate variables captured	Selected References
Natural archives	Lake and river sediments	Sediment laminations, charcoal, slackwater deposits, remains of organisms such as diatoms, foraminifera, microbiota, pollen	Decades to centuries	Millions	Summer temperature, winter snowfall, rainfall, flood events, wind patterns	Mills *et al* (2017), Leng and Marshall (2004), Gibson *et al* (2016), Morrill (2004), Barr *et al* (2014), Lam *et al* (2017), Saunders *et al* (2018)
	Marine sediments	Physical and chemical properties, shells, pollen, foraminifera, molecular fossils, isotopes	Centuries to millennia	Tens of millions	Temperature	Westerhold *et al* (2021), Elderfield and Ganssen (2000)
	Ice Cores (from ice sheets and glaciers)	Stable isotopes, various salts and acids concentration, implied atmospheric loading of dust pollen, and trace gases (e.g. CH4 and CO2)	Yearly to seasonal	Hundreds	Temperature, precipitation, atmospheric composition, volcanic activity, wind patterns, greenhouse gases	Eichler *et al* (2009), Meese *et al* (1994), Opel *et al* (2018), Porter *et al* (2016)
	Tree rings	Tree-ring width, wood density, stable isotopes, wood anatomy, some trace elements	Yearly	Thousands	Temperature, precipitation, flood, drought	Allen *et al* (2018), McCarroll and Loader (2004), Cook *et al* (2016), Schneider *et al* (2015), Aznar *et al* (2008)
	Speleothems	Physical and chemical laminations, stable isotopes	Decades to centuries	Tens of thousands	Environmental conditions	Fairchild and Baker (2012), Fischer (2016)
	Corals, sclerosponges, and mollusks	Elemental and isotopic analysis, geochemical properties, growth rate	Annual to monthly	Centuries	Sea surface temperature environmental conditions	Abram *et al* (2020), Black *et al* (2019), Corrège (2006), Sadler *et al* (2014)
	Pack rat middens	Pollen, insects, plant remnants, bones, teeth, isotopes	Decades	Tens of thousands	Environmental conditions	Betancourt *et al* (1991), Smith *et al* (2021)
Historical archives	Historical documents	annals, chronicles, memorial books, memoirs, newspapers, journals, diaries, accounting books or weather journals, pamphlets, technical reports, flood maps, images	Hours to days	Hundreds	Flood, drought, temperature, precipitation, wind, cyclone, tsunami	Brázdil *et al* (2018), Dobrovolny *et al* (2010), Glaser (2008), Pfister (2009)
	Archaeological record	Sites and associated metadata (e.g. site size, location and organisation), artefacts and associated metadata (function, provenance), landscape modifications (e.g. irrigation systems, terraces) stratigraphic evidence, radiometric dates	Hours to millions of years	Hundreds to tens of thousands	Flood/sea-level change, drought, temperature, tsunami, volcanic eruption, earthquake	Hussain and Riede (2020), Sandweiss and Kelley (2012), Caseldine and Turney (2010)

Table 3. Specific indicators for which palaeo-data could provide input. Although the long-term data has generally not been directly obtained using the methodology outlined for the Indicators (e.g. www.unstats.un.org/sdgs/metadata), and nor is it universally available for all relevant locations in all countries, it nevertheless still provides vital background information that can inform the development of indicators. It also provides long-term variability information, highly relevant for improving our understanding of slow variables and how they respond to either external or internal change.

SDG	Indicator	Indicator description	Examples of relevant palaeo studies
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture	2.2.1	Prevalence of undernourishment	Malnutirtion, health (Hegmon *et al* 2008, Carson and Hung 2018)
	2.4.1	Proportion of agricultural area under productive and sustainable agriculture	Land use systems (Carson *et al* 2015, Carson and Hung 2018)
6. Ensure availability and sustainable management of water and sanitation for all	6.3.2	Proportion of bodies of water with good ambient water quality;	Human impacts on water resources (Gouramanis *et al* 2010, Batterbee *et al* 2012, Dubois *et al* 2018)
	6.4.2	Level of water stress: freshwater withdrawal as a proportion of available freshwater resources;	Groundwater depth (Gouramanis *et al* 2010)
	6.6.1	Change in the extent of water related ecosystems over time;	Prevalence of drought/pluvial conditions (Cook *et al* 2007, Cook *et al* 2010, Palmer *et al* 2015, Cook *et al* 2016, Stahle *et al* 2016)
9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	9.4.1	CO2 emission per unit of value added	CO2 records through time (Kaplan *et al* 2010, Masson-Delmotte *et al* 2013)
11. Make cities and human settlements inclusive, safe, resilient and sustainable	11.3.1	Ratio of land consumption rate to population growth rate;	Reconstruction of population change/density (Peros *et al* 2010, Freeman *et al* 2020, Keenan *et al* 2021), land use change (Carson and Hung 2018)
	11.6.2	Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities	Lead, atmospheric pollution (Zennaro *et al* 2014, Chen *et al* 2016, Chen *et al* 2020, Rose 2015)
13. Take urgent action to combat climate change	13.3.1	Number of countries that have integrated mitigation, adaptation, impact reduction and early warning into primary, secondary and tertiary education	Issues of Anthropocene impacts integrated into historical/archaeological curricula (McCorriston and Field 2020, Riede 2022)
	13.2.2	Total greenhouse gas emissions per year	See IPCC 2021 and references therein
14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development	14.1.1 (a&b)	Index of coastal eutrophication	Coastal eutrophication (Ivarsson *et al* 2019), changes in lake health (Smol *et al* 2001b)
	14.3.1	Average marine acidity (pH) measured at agreed suite of representative sampling stations	Ocean acidification (Hönisch *et al* 2012)
15. Protect, restore and promote sustainable use of terrestrial ecosystems, manage forests, combat desertification, and halt and reverse land degradation, and halt biodiversity loss	15.1.1	Forest area as a proportion of total land area;	Deforestation, forest expansion (Rolett and Diamond 2004, Campbell 2016, Ellis *et al* 2021, Kaplan *et al* 2010, Stephens *et al* 2019)
	15.3.1	Proportion of land that is degraded over total land area.	Land degradation (Kiage and Liu 2009, Willis *et al* 2015, Fei *et al* 2019, Mischke *et al* 2019)

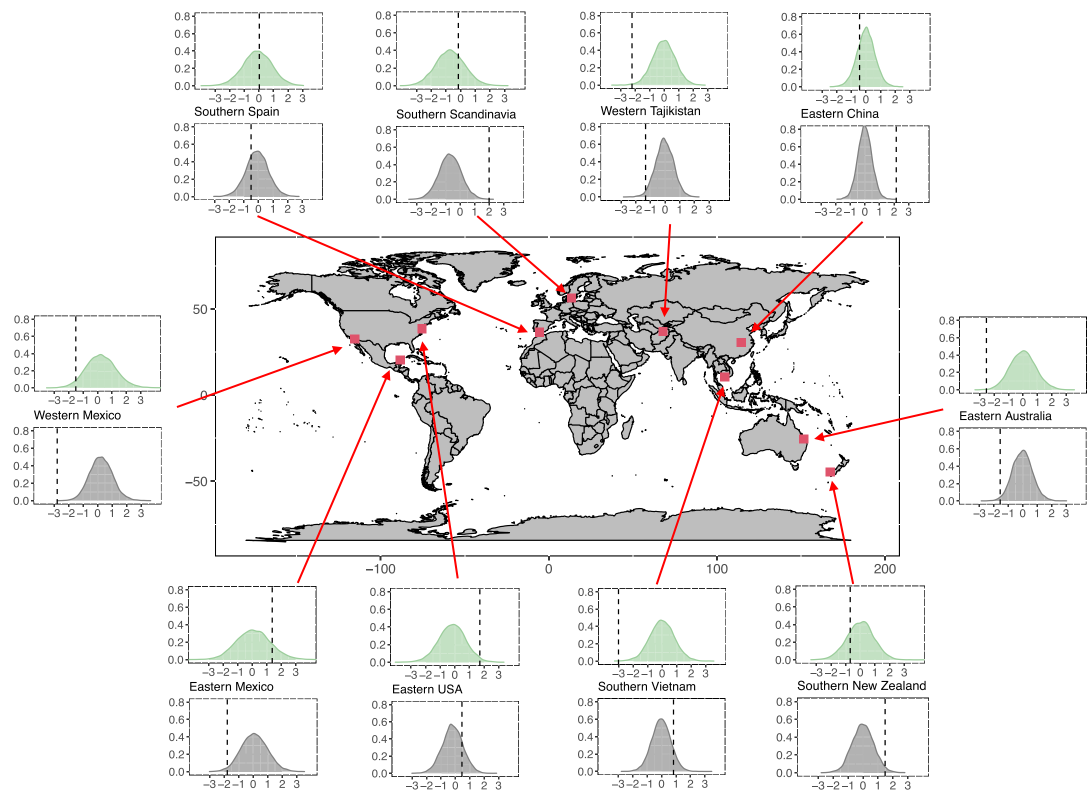

Figure 2. Comparison of average hydroclimate conditions over the 2000–2004 and 2016–18 baselines relevant for Target 6.6 (By 2020, protect and restore water-related ecosystems') with distributions of 10 000 five- and three year mean hydroclimate for 3° × 3° areas around selected RAMSAR-listed wetlands (www.rsis.ramsar.org). hydroclimate conditions obtained from tree-ring based drought atlases (based on the self-calibrating palmer drought severity index) for North America (Cook *et al* 2007), Mexico (Stahle *et al* 2016), Europe (Cook *et al* 2016), Asia (Cook *et al* 2010) and eastern Australia/New Zealand (Palmer *et al* 2015). Green distributions are based on three year means (i.e. 2016–18 baseline), and grey distributions are based on the five year mean (i.e. the 2000–2004 baseline). Dashed vertical lines show where the baseline value sits relative to the distribution. Selected areas include: Yucatan/Campeche in Mexico (several wetlands); far northwest of Mexico includes several wetlands including Laguna Hanson, Estero de Punta Banda, Hunedales Delta del Rio Colorado; Eastern USA area includes Delaware bay Estuary, Chesapeake Bay Estuarine Complex and Edwin B Forsythe National Wildlife Refuge; Pyandi River area in Tajikistan; Awarua wetland in New Zealand; Great Sandy Strait in eastern Australia; area including U Mint Thuong and Cam Mau National Parks in Vietnam; area covering southern Sweden and eastern Denmark contains multiple wetlands; area around Cadiz in southern Spain contains several wetlands.

hydroclimate reconstructions further demonstrate that more severe and/or protracted droughts and more severe floods than those observed over the past century have previously occurred (Baker 1998, Cook *et al* 2007, 2016, Wilhelm *et al* 2013, Palmer *et al* 2015, Stahle *et al* 2016, St George *et al* 2020, O'Donnell *et al* 2021, Ionita *et al* 2021, Cook *et al* in review, and references therein), or, in the case of South America, that recent hydroclimate variability is unprecedented over the past 600 years (Morales *et al* 2020).

Secondly, a universal baseline for Indicator 6.6.1 ignores the spatial heterogeneity of the impacts of natural climate variability and change (figure 2; Willis and Bhagwat 2009, Peterson *et al* 2013, Blaquez *et al* 2015, Dearing *et al* 2015, Campbell 2016, Falk *et al* 2019). This may result in potentially unrealistic comparisons across regions and inappropriate policy prescriptions. Regionally specific baselines will better contexturalise risk, and hence vulnerability to events relevant for specific regions (e.g. floods in low-lying areas or variation in major climate systems like ENSO). These two issues demonstrate the importance of considering how boundary conditions change over both temporal and spatial scales when aiming to build resilience (Gillson *et al* 2021; figure 1). Data over long time frames is also required to assess social-ecological impacts of nested climate events (Harris *et al* 2018) and projected cascading crises (IPCC 2022).

Moving (Folke *et al* 2010) and/or baselines premised on periods when the environment has already been heavily altered can also be highly problematic (Falk *et al* 2019, Gillson *et al* 2021). For example, palaeo-data over 7000 years indicates that a 1985 baseline against which wetland salinity for one wetland in the Australian Murray-Darling Basin was measured was far too high. This inadvertently contributed to ecological collapse rather than improved resilience (Gillson *et al* 2021). In some cases, scale-dependent notions of resilience rather than a single reference point may be more appropriate because it cannot be assumed that recent conditions have been optimal for a particular system (Falk et al 2019). Building resilience requires flexibility, an openness to learning and an understanding of the slow variables underlying system dynamics (Folke et al 2010, Dearing et al 2015). Palaeodata can capture temporal lags, internal and external variability to which slow variables respond over long time frames (Wang et al 2012 amongst others) thus providing a clear rationale for the serious consideration of pre-instrumental-era records, especially in relation to SDGs 6, 9, 11, 13, 14 and 15.

As a reference for progress towards the relevant SDGs, establishing appropriate means of measuring progress against indicators has enormous importance. This task requires a sound grasp of spatial and temporal variability across scales and the complexity of direct, indirect and lagged effects upon which global, regional and local processes act and respond to anthropogenic change (indicator 13.3.1). This highlights a need for much greater palaeo-literacy by planners and decision makers, and such palaeo-literacy is an important part of an inclusive education about climate change (SDG indicator 13.3.1; table 3). Improved palaeo-literacy would support development and implementation of global, national, regional and local policies that encompass pre-industrialisation environmental conditions, natural versus non-natural variability and trajectories, resilience and buffering capacities, and rates of recovery post-disturbance (e.g. Rockstrom et al 2009; table 3). Palaeo-data would also be useful in the global south where observational data is scant or of very short duration.

1.2. The relevance of archaeological and historical information for the SDGs

Palaeoclimate data informs us that abrupt changes or reaching major tipping points will have extensive climate impacts. For example, changes in the Atlantic Meridional Overturning Circulation, affect the west African and east Asian monsoons, the Amazon basin, and contribute to heat build-up in the Southern Ocean with cascading impacts on the Antarctic ice-sheet, major fisheries and food production (Dahl et al 2005, Hu et al 2015). By itself, however, palaeoclimate data does not elaborate on the resilience of past societies to abrupt change. Extensive historical and archaeological data from across the Holocene (the last ∼11 700 years) yields significant insight, however (Brovkin et al 2021). 'Abrupt' climate change can occur across a variety of temporal (e.g. tens to hundreds of years) and spatial (i.e. local, regional, and global) scales. Additionally, as responses of social-ecological systems to abrupt change can occur over much longer time frames than decadal (e.g. Spate 2019), it is highly relevant to consider a variety of time scales.

The overarching lesson that can be drawn from historical and archaeological records is that social-ecological responses to abrupt change are always context dependent, with vulnerability and exposure to even moderate climate shocks mediated by social and political institutions. They often result in marked social change even if some delay occurs (e.g. Staubwasser and Weiss 2006, O'Brien et al 2007, Hegmon et al 2008, Campbell 2016, Nelson et al 2016, Wang et al 2016, Flohr et al 2016, Allcock 2017, Challinor et al 2017, Danti 2018, Di Cosmo et al 2018, Haldon et al 2018, Bal 2019, Frenkel 2019, Kleijne et al 2020, Yang et al 2019, Peregrine 2020, Burke et al 2021, Degroot et al 2021). Moderate shocks such as the Little Ice Age and Late Antique Little Ice Age were associated with widespread famine and disease, repeated harvest failure in many regions, geopolitical shifts, regional migration, major changes in land use and changing religious inclinations (see Gunn 2000, Høilund Nielsen 2005, Nunn et al 2007, Pfister 2009, Löwenborg 2012, Bondeson and Bondesson 2014, Tvauri 2014, Degroot 2015, Price and Graslund 2015, Büntgen et al 2016, Campbell 2016, Sadowski 2020). Yet, in many other cases, societies proved resilient to abrupt (whether over decadal or centennial scales) climate change (Yang et al 2019 and references therein, 2021, Degroot et al 2021). Through analysis of the cluster of volcanic eruptions occurring between 1637 and 1646, during the final stages of the Thirty Years' War (1618–1648), Stoffel et al (2022) offer a textbook example of difficulties in attributing political instability, harvest failure and famines solely to volcanic climatic impacts. This example shows that it is time to move past reductive framings in which climate (and environment more broadly) either is or is not deemed an important contributor to major historical events. Below we briefly outline some specific points that repeatedly arise in the historical and archaeological literature that are relevant to the SDGs (figure 3).

2. Learning, experimentation and innovation

Retaining, valuing, expanding and enriching cultural knowledge while encouraging innovation are fundamentally part of the SDG framework (SDGs 4 and 9, Target 13.3 and implicitly, SDGs 2–3, 6, 11–17; figure 3). Together, a wide range of palaeoclimate and archaeological records highlight the importance of learning and innovation. Changes in land and water management practices, crops grown, and technological change across many regions (e.g. the North Atlantic, Middle-East, Mediterranean, South America, Asia, Europe) in response to abrupt climatic downturns or sequences of downturns, changes in seasonality at decadal to centennial-scales throughout the Holocene contributed to resilience of many societies (Szczesny 2016, Marsh et al 2017, Warden et al 2017, Riris and Arroyo-Kalin 2019, Cheung et al 2019, Crombe 2019, Deom et al 2019,

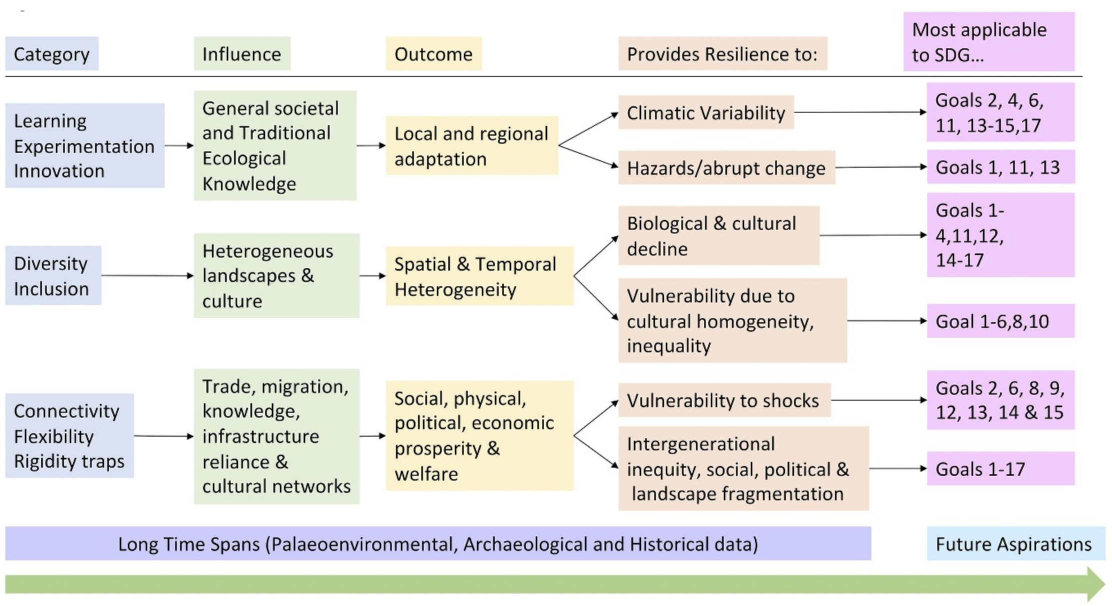

Figure 3. Schematic showing pathways by which information in historical and archaeological records—as categorised in the manuscript—become relevant to the SDGs.

Panyushkina *et al* 2019, Ran and Chen 2019, Klejines *et al* 2020, Petraglia *et al* 2020, Grocutt *et al* 2021 amongst many others). The lack of evidence for widespread societal collapse along the Silk Road during the 8.2 and 9.2 ka events points to the success of local adaptation (Yang *et al* 2019). Traditional ecological knowledge based on retained knowledge, innovation, social networks and bottom-up decision making has also contributed to adaptation of Indigenous peoples to climatic variability and abrupt change (figure 1; Adger *et al* 2009, Pearce *et al* 2015).

3. Diversity and inclusion

As a theme, broadening diversity and inclusion permeates the SDGs, both explicitly (SDGs 4-11, 14–15) and implicitly (SDGs 1-3, 12, 16–17). Ample evidence in archaeological and historical records supports the core relevance of cultural diversity and inclusion (Burke *et al* 2021; figure 3) in resilient social-ecological systems (e.g. Hegmon *et al* 2008, Szczesny 2016, de Majo 2019, Klassen and Evans 2020, Burke *et al* 2021, Grocutt *et al* 2021). Greater political participation after disaster has resulted in less conflict and helped preserve structures that bonded groups together (Peregrine 2018). It has also improved flexibility, experimentation, and matching of problems and solutions (Mostert 2012, de Majo 2019), although challenges exist (e.g. Mostert 2012). In contrast, declining cultural diversity and inclusion and increasing centralisation have often been observed immediately prior to social-ecological collapse in many instances (e.g. Hegmon *et al* 2008, Szczesny 2016, Peregrine 2018, Klassen and Evans 2020, Sadowski 2020, Grocutt *et al* 2021, Scheffer *et al* 2021).

Recognition of the importance of spatial heterogeneity of the physical environment and impacts of abrupt climate change is equally important (see figure 2). This heterogeneity has facilitated food diversification strategies and trade, important aspects of promoting resilience (Riris and Arroyo-Kalin 2019, Spate 2019, Xu *et al* 2020, Hall 2021)—and is today under pressure from, for instance, monocultural cash-cropping, wage labour or herd expansion. Greater inclusion of Indigenous peoples to develop more holistic approaches that respect heterogeneous landscapes, promote biodiversity and culture will also promote biological and cultural diversity (figure 1; Desjardins *et al* 2020, Petzold *et al* 2020, Burke *et al* 2021, Fletcher *et al* 2021).

4. Connectivity, flexibility and rigidity traps

Sachs *et al* (2019) outline six critical and multifaceted transformations required to achieve the SDGs. These transformations require interrelated and complex long-term changes and well-coordinated implementation (Sachs *et al* 2019). In other words, a high degree of connectivity is required for the implementation of the SDGs. Extensive evidence demonstrates the importance of connectivity for resilience through cultivation of extensive trade, migration, knowledge and cultural networks that provided support in times of need (Hegmon *et al* 2008, Cooper and Peros 2010, Degroot 2015, Hall 2021, Nelson *et al* 2016, Szczesny 2016, Waldinger 2015, Peregrine 2018, Weiberg and Finnè 2018, Bal 2019, Klejine *et al* 2020, Torrence 2020, Grocutt *et al* 2021, Jariel 2021, Yang *et al* 2021). Cessation or decline of connective networks has been associated with a loss of resilience, decreased innovation and diversity and increased conflict (Nunn *et al* 2007, Hegmon *et al* 2008, Waldinger 2015, Sadowski 2020, Jariel 2021). Increasingly fragmented landscapes can lead to biodiversity loss from which other impacts cascade (Chase *et al* 2020). In some cases, however, increased flexibility has resulted in self-serving local elites (Campbell 2016).

Failure to manage complexity and interrelatedness through more favourable times, however, can contribute to rigidity traps (Holling and Gunderson 2002, Rogers *et al* 2012, Allcock 2017). Over-reliance on established and complex social, physical and/or political infrastructure and procedures can pose significant barriers to continued prosperity and welfare of societies, especially as shocks—e.g. climate change—occur (Holling and Gunderson 2002). The extensive physical infrastructure buffering complex societies such as Angkor or Mesa Verde against variability were ultimately short-term buffers that effectively precluded required transformations (Hegmon *et al* 2008, Klassen and Evans 2020). Such buffers can shield parts of social-ecological systems from collapse even as a business-as-usual approach exhibits strong signs of slowing and increasing vulnerability (Hegmon *et al* 2008, Folke *et al* 2010, Redman 2012, Penny *et al* 2018, Weiberg and Finnè 2018, Klassen and Evans 2020, Grocutt *et al* 2021, Scheffer *et al* 2021).

Similarity in trajectories of societal decline or collapse across multiple societies and time periods highlights the potential dangers of our highly interconnected and interdependent modern systems. COVID-19 and the rapid spread of other pests and diseases pose challenges to this elevated interdependence, increasing our vulnerability to abrupt change (Li 2020). Failure of a single link in highly interconnected trade and production networks can create extensive disruptions, increasing vulnerability to shocks (Challinor *et al* 2017). Managing levels of connectivity and flexibility is particularly relevant for SDGs 2, 6, 8, 9, 12–15 (figure 3) to avoid promoting short term buffers that simply increase long-term vulnerability and reduce intergenerational equity (Lim *et al* 2018). High levels of complexity in administrative and implementation structures for the SDGs may be similarly problematic.

4.1. Discussion and conclusions

Our purpose here has been to demonstrate to policy makers and managers that together, palaeo data, archaeological and historical records point to a number of key factors that promote resilience and are relevant to the SDG framework and its implementation. We draw on the cited examples to outline three fundamental lessons from long-term memory.

The first is the much-commented upon friction between SDG8 and part of SDG9 (industrialisation) with the planetary SDGs 6, 13–15 that has flow-on consequences for environmental justice (Hickel 2018, Menton *et al* 2020, Skene 2021). Evidence from the past shows that expansion of human activity has adversely impacted the environment through desiccation and deforestation, and that these impacts can be amplified by abrupt onset of adverse climate conditions (see Campbell 2016, Cook *et al* in review, Allcock 2017, Challinor *et al* 2017, Fei *et al* 2019, Mischke *et al* 2019, Stephens *et al* 2019). Apparently flourishing societies can persist beyond critical environmental tipping points despite their increasing vulnerability to collapse (Allen *et al* 2019, Weiberg and Finnè 2018, Scheffer *et al* 2021). A piecemeal focus on achieving individual SDGs ultimately ignores potential conflict inherent within the SDGs themselves and their fragility vis-a-vis climate extremes and natural hazards (Reichstein *et al* 2021).

Secondly, the SDGs are consistent with a view that social-ecological systems will readily adapt to abrupt climate change and its impacts given technological and economic constraints (e.g. Reilly and Schimmelpfennig 2000). However, the failure by the OECD countries to overcome major challenges to combating climate change, suggests our current direction around the feedback loop is anti-clockwise (figure 1), retarding progress towards several SDGs (cf IPCC 2022). In the past, abrupt climate changes have typically been associated with increased inequality (Scanlon 1988, Sheets 2020), and current climate change is reversing progress made towards greater equity, food and water security and improved health (Romanello *et al* 2021, IPCC 2022). Incremental changes in climate are also increasingly challenging agricultural potential, equality and health outcomes in many regions (Ramankutty *et al* 2002, Lesk *et al* 2016, Challinor *et al* 2017, Romanello *et al* 2021, IPCC 2022). Additionally, concerns exist that emissions overshoots will occur due to COVID-19 recovery plans while the epidemic continues to disproportionately affect the most disadvantaged (Romanello *et al* 2021). Without an applied understanding of long-term impacts of shocks, and long-term trajectories of change, adaptation, collapse and resilience, and why some societies have succeeded or failed in responding to these shocks, the capacity of the SDG framework to improve resilience over medium—long time frames may be compromised (see Quiggan *et al* 2021).

Thirdly, using universal shallow baselines that do not recognise inherent diversity in social-ecological systems against which to measure progress in relation to specific targets is likely to result in inappropriate measures of progress in many cases, and potentially environmental degradation (SDGs 6, 14–16; Gillson *et al* 2021). This will especially be the case when processes of change are underlain by long-term variability.

Projections indicate that within 50 years temperatures will move outside the narrow de facto human tolerance envelope of the past 6000 years (Xu *et al* 2020), emphasising the urgency of combating climate change. Climate change threatens the resilience that increased diversity and inclusion, improved equity and education, improved infrastructure, justice and a healthy physical environment can provide. Even moderate climatic downturns in the past have led to major societal decline. We must therefore ask whether the current configuration of societal and organisational structures and priorities, and changes embodied in the SDGs, sufficiently support actions to provide the resilience and willingness required to successfully address climate change (clockwise direction, figure 1). Or, will that structural configuration, priorities and the scale of climate change, overwhelm the resilience measures embodied in the SDGs (anti-clockwise direction, figure 1)? Our assessment here is a timely reminder of the power of the past to illuminate future directions as the SDGs are being increasingly translated into policies, actions and education agendas (Kelman 2017, Rees 2017, Stewart and Gill 2020). Although such long-term data cannot provide all answers, it does shine a critical light on what has and has not previously promoted social-ecological resilience and informs measures of progress.

In conclusion, we highlight four key messages:

(a) The relationship amongst climate change, the SDGs and resilience can be broadly considered a positive feedback loop (figure 1). To achieve progress towards the resilience, we need to travel in a clockwise direction.
(b) Variability and change over long time frames are inherent in natural, and human, systems. It is therefore essential to incorporate the information from the wealth of palaeo-records available into frameworks purporting to measure progress towards resilience.
(c) Analysis of historical and archaeological records over long time spans and in relation to specific events is critical to informing policies that aim to increase our resilience to the accumulating impacts of change.
(d) We need to very carefully assess what records of the past tell us about the potential conflict between planetary and some social goals. Where long-term records indicate persistent clashes in objectives, we need to be sufficiently bold to robustly address these challenges in order to avoid promoting an anti-clockwise journey around the feedback loop.

Data availability statement

No new data were created or analysed in this study.

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References

Abram N J *et al* 2020 Coupling of Indo-Pacific climate variability over the last millennium *Nature* **579** 385–97
Adger W N, Lorenzoni I and O'Brien K L 2009 Adaptation now *Adapting to Climate Change: Thresholds, Values, Governance* ed W N Adger, I Lorenzoni and K L O'Brien (Cambridge: Cambridge University Press) ch 1, pp 1–22
Allcock S L 2017 Long-term socio-environmental dynamics and adaptive cycles in Cappadocia, Turkey during the Holocene *Quat. Int.* **446** 66–82
Allen C R, Angeler D G, Chaffin B C, Twidwell D and Garmestani A 2019 Resilience reconciled *Nat. Sustain.* **2** 898–900
Allen K J, Cook E R, Francey R J, Buckley B M, Palmer J G, Peterson M J and Baker P J 2018 Lack of cool, not warm extremes distinguishes late 20th century climate in 979-year tasmanian summer temperature reconstruction *Environ. Res. Lett.* **13** 3
Allen K J, Hope P, Lam D, Brown J R and Wasson R J 2020 Improving Australia's flood record for planning

purposes—can we do better? *Australas. J. Water Resour.* **24** 36–45
Andrijevic M, Cuaresma J C, Muttarak R and Schleussner C F 2020 Governance in socioeconomic pathways and its role for future adaptive capacity *Nat. Sustain.* **3** 35–41
Aznar J-C, Richer-Lafléche Bégin C and Rodrigue R 2008 Spatiotemporal reconstruction of lead contamination using tree rings and organic soil layers *Sci. Total Environ.* **15** 233–41
Baker V 1998 Hydrological understanding and societal action *J. Am. Water Resour. Assoc.* **34** 819–25
Bal C 2019 The impact of the 4.2 ka BP event in western Anatolia: an evaluation through palaeoenvironmental and archaeological data *Master of Science Thesis* Middle East Technical University
Barr C, Tibby J, Gell P, Tyler J, Zawadzki A and Jacobsen G 2014 Climate variability in south-eastern Australia over the last 1500 years inferred from the high-resolution diatom records of two crater lakes *Quat. Sci. Rev.* **95** 115–31
Barthel S, Crumley C L and Svedin U 2013 Bio-cultural refugia—safeguarding diversity of practices for food security and biodiversity *Glob. Environ. Change* **23** 1142–52
Batterbee R W, Anderson N J, Bennion H and Simpson G L 2012 Combining limnological and palaeolimnological data to disentangle the effects of nutrient pollution and climate change on lake ecosystems: problems and potential *Freshw. Biol.* **57** 2091–106
Berkes F, Colding J and Folke C 2000 Rediscovery of traditional ecological knowledge as adaptive management *Ecol. Appl.* **10** 1251–62
Betancourt J L, Van Devender T R and Martin P S (eds) 1991 *Packrat Middens: The Last 40,000 Years of Biotic Change* (Tucson, AZ: University of Arizona) (available at: www.biodiversitylibrary.org/part/171122)
Black B A *et al* 2019 The revolution of crossdating in marine palaeoecology and palaeoclimatology *Biol. Lett.* **15** 20180665
Blaquez O, AA A, Giardin M P, Grondin P, Frèchette B, Bergeron Y and Hèly C 2015 Regional paleofire regimes affected by non-uniform climate, vegetation and human drivers *Sci. Rep.* **5** 13356
Bliege Bird R and Bird D W 2021 Climate, landscape diversity, and food sovereignty in arid Australia: the firestick farming hypothesis *Am. J. Hum. Biol.* **33** e23527
Bondeson L and Bondesson T 2014 On the mystery cloud of AD 536, a crisis in dispute and epidemic ergotism: a linking hypothesis *Danish J. Archaeol.* **3** 61–67
Bradley K *et al* 2019 Earthquake-triggered 2018 Palu Valley landslides enabled by wet rice cultivation *Nat. Geosci.* **12** 935–9
Brázdil R, Kiss A, Luterbacher J, Nash D J and Řezníčková L 2018 Documentary data and the study of the past droughts: an overview of the state of the art worldwide *Clim. Past* **14** 1915–60
Brovkin V *et al* 2021 Past abrupt changes, tipping points and cascading impacts in the Earth system *Nat. Geosci.* **14** 550–8
Buckley B M, Anchukaitis K J, Penny D, Fletcher R, Cook E R, Sano M, Canh Nam L, Wichienkeeo A, That Minh T and Mai Hong T 2010 Climate as a contributing factor in the demise of Angkor, Cambodia *Proc. Natl Acad. Sci. USA* **107** 6748–52
Büntgen U *et al* 2016 Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD *Nat. Geosci.* **9** 231–6
Burke A, Peros M C, Wren C D, Pausata F S R, Riel-Salvatore J, Moine O, de Vernal A, Kageyama M and Boisard S 2021 The archaeology of climate change: the case for cultural diversity *Proc. Natl Acad. Sci.* **118** e2108537118
Cai Y, Lenton T M and Lontzek T S 2016 Risk of multiple interacting tipping points should encourage rapid CO2 emission reduction *Nat. Clim. Change* **6** 520–5
Campbell B M S 2016 *The Great Transition: Climate Disease and Society in the Late-Medieval World* (Cambridge: Cambridge University Press) pp 463
Carson J F, Watling J, Mavle F E, Whitney B S, Iriarte J, Prümers H and Soto J D 2015 Pre-columbian land use in the ring-ditch region of the Bolivian Amazon *Holocene* **25** 1285–300
Carson M T and Hung H 2018 Learning from paleo-landscapes: defining the land-use systems of the ancient Malayo-Polynesian homeland *Curr. Anthropol.* **59** 790–813
Caseldine C and Turney C S M 2010 The bigger picture: towards integrating palaeoclimate and environmental data with a history of societal change *J. Quat. Sci.* **25** 88–93
Challinor A J, Adger W N and Benton T G 2017 Climate risks across borders and scales *Nat. Clim. Change* **7** 621–3
Chase J M, Blowes S A, Knight T M, Gerstner K and May F 2020 Ecosystem decay exacerbates biodiversity loss with habitat loss *Nature* **584** 238–49
Chen M, Boyle E A, Switzer A D and Gouramanis C 2016 A sedimentary record of the anthropogenic lead (Pb), Pb isotopes and other trace metals from the Singapore region *Environ. Pollut.* **213** 446–59
Chen Q, McGowan S, Gouramanis C, Fong L S, Balasubramanian R and Taylor D 2020 A possible doubling of non-biomass burning-related transboundary atmospheric pollution in Singapore and its implications for sustainable development in Southeast Asia *Environ. Res. Lett.* **15** 1040a5
Cheung C, Zhang H, Hepburn J C, Yang D Y and Richards M P 2019 Stable isotope and dental caries data reveal abrupt changes in subsistence economy in Ancient China in response to global climate change *PLoS One* **14** e0218943
Codding B F, Bird R B, Kauhanen P G and Bird D W 2014 Conservation or co-evolution? Intermediate levels of aboriginal burning and hunting have positive effects on kangaroo populations in Western Australia *Hum. Ecol.* **42** 659–69
Colding J and Barthel S 2019 Exploring the social-ecological systems discourse 20 years later *Ecology and Society* **24** 2
Convention on Wetlands 2021 *Global Wetland Outlook: Special Edition 2021* (Gland: Switzerland Secretariat of the Convention on Wetlands) p 54
Cook B *et al* Megadroughts in the common Era and the anthropocene *Nat. Rev. Earth Environ.* in review
Cook E R *et al* 2016 Old world megadroughts and pluvials during the common Era *Sci. Adv.* **1** e150056
Cook E R, Anchukaitis K J, Buckley B M, D'Arrigo R D, Jacoby G C and Wright W E 2010 Asian monsoon failure and megadrought during the last millennium *Science* **328** 486–9
Cook E R, Seager R, Cane M A and Stahle D W 2007 Norther American drought: reconstructions, causes and consequences *Earth Sci. Rev.* **81** 93–134
Cooper J and Peros M 2010 The archaeology of climate change in the Caribbean *J. Archaeol. Sci.* **37** 1226–32
Corrège T 2006 Sea surface temperature and salinity reconstruction from coral geochemical tracers *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **232** 408–28
Cote M and Nightingale A J 2012 Resilience thinking meets social theory: situating social change in socio-ecological systems (SES) research *Prog. Hum. Geogr.* **36** 475–89
Crombe P 2019 Mesolithic projectile variability along the southern North Sea basin (NW Europe): hunter-gatherer responses to repeated climate change at the beginning of the holocene *PLoS One* **14** e0219094
Dahl K A, Broccoli A J and Stouffer R J 2005 Assessing the role of North Atlantic freshwater forcing in millennial scale climate variability: a tropical perspective *Clim. Dyn.* **24** 325–46
Danti M D 2018 Late middle holocene climate and northern mesopotamia: varying cultural responses to the 5.2 and 4.2 ka aridification events *Climate Crises in Human History* ed A B Mainwaring, R Giegengack and Vita-Finzi C (Philadelphia, PA: American Philosophical Society) ch 8, pp 139–72
De Majo C 2019 Understanding the Southern Italian commons: polycentric governance on the mountains of sila *Modern* **24** 331–48

Dearing J A et al 2015 Social-ecological systems in the anthropocene; the need for integrating social and biophysical records at regional scales *Anthr. Rev.* **2** 220–46
Degroot D 2015 Change and society in the 15th to 18th centuries *WIREs Clim. Change* **9** e518
Degroot D et al 2021 Towards a rigorous understanding of societal responses to climate change *Nature* **591** 539–50
Deom J M, Sala R and Laudisoit A 2019 The Ili River delta: holocene hydrogeological evolution and human colonization *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H-R Bork, X Fang and S Mischke (Cham: Springer Nature) ch 4, p 506
Desjardins S P A, Friesen T M and Jordan P D 2020 Looking back while moving forward: how past responses to climate change can inform future adaptation and mitigation strategies in the Arctic *Quat. Int.* **549** 239–48
Di Cosmo N, Hessl A, Leland C, Byambasuren O, Tian H, Nachin B, Pederson N, Andreu-Hayles L and Cook E R 2018 Environmental stress and steppe nomads: rethinking the history of the Uygher Empire (744–840) with paleoclimate data *J. Interdiscip. Hist.* **48** 439–63
Dobrovolny P et al 2010 Monthly, seasonal and annual temperature reconstructions for central Europe derived from documentary evidence and instrumental records since AD1500 *Clim. Change* **101** 69–107
Dubois N et al 2018 First human impacts and responses of aquatic systems: a review of palaeolimnological records from around the world *Anthr. Rev.* **5** 28–68
Eichler A, Brütsch S, Olivier S, Papina T and Schwikowski M 2009 A 750 year ice core record of past biogenic emissions from Siberian boreal forests *Geophys. Res. Lett.* **36** L18813
Elderfield H and Ganssen G 2000 Past temperature and δ^{18}O of surface ocean waters inferred from foraminiferal Mg/Ca ratios *Nature* **405** 442–5
Ellis E C et al 2021 People have shaped most of terrestrial nature for at least 12,000 years *Proc. Natl Acad. Sci. USA* **118** e2023483118
Fairchild I and Baker A 2012 *Speleothem Science: From Process to Past Environments* (New York: Wiley) p 432
Falk D A, Watts A C and Thode A E 2019 Scaling ecological resilience *Front. Ecol. Evol.* **7** 275
Fedele G, Donatti C I, Harvey C A, Hannah L and Hole D G 2019 Transformative adaptation to climate change for sustainable social-ecological systems *Environ. Sci. Policy* **101** 116–25
Fei J, He H, Yang L E, Yang S and Zhou J 2019 Evolution of saline lakes in the Guanzhong Basin during the past 2000 years: inferred from historical records *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H-R Bork, X Fang and S Mischke (Cham: Springer Nature) ch 2, p 506
Fischer M J 2016 Predictable components in global speleothem δ^{18}O quaternary *Sci. Rev.* **131** 380–92
Fletcher M-S, Hamilton R, Dressler W and Palmer L 2021 Indigenous knowledge and the shackles of wilderness *Proc. Natl Acad. Sci.* **118** e202218118
Flohr P, Fleitmann D, Matthews R, Matthews W and Black S 2016 Evidence of resilience to past climate change in southwest Asia: early farming communities and the 9.2 and 8.2 ka events *Quat. Sci. Rev.* **136** 23–39
Folke C S, Colding J and Berkes F 2002 Synthesis: building resilience and adaptive capacity in social-ecological systems *Navigating Social-Eoclogical Systems* ed F Berkes, J Colding and C Folke (Cambridge: Cambridge University Press) ch 14, p 393
Folke C 2006 Resilience: the emergence of a perspective for social–ecological systems analyses *Glob. Environ. Change* **16** 253–67
Folke C, Carpenter S R, Walker B H, Scheffer M, Elmqvist T, Gunderson L H and Holling C S 2004 Regime shifts, resilience, and biodiversity in ecosystem management *Annu. Rev. Ecol. Evol. Syst.* **35** 557–81
Folke C, Carpenter S R, Walker B, Scheffer M, Chapin T and Rockström J 2010 Resilience thinking: integrating resilience, adaptability and transformability *Ecology and Society* **15** 20
Freeman J, Robinson E, Beckman N G, Bird D, Baggio A and Anderies J M 2020 The global ecology of human population density and interpreting changes in paleo-population density *J. Archaeol. Sci.* **120** 105168
Frenkel Y 2019 The coming of the barbarians: can climate explain the Saljjuqs' advance? ed L E Yang, H-R Bork, X Fang and S Mischke *Socio-Environmental Dynamics along the Historical Silk Road* (Cham: Springer Nature) ch 13, p 506
Gibson J J, Birks S J, Yi Y, Moncur M C and McEachern P M 2016 Stable isotope mass balance of fifty lakes in central alberta: assessing the role of water balance parameters in determining trophic status and lake level *J. Hydrol.: Reg. Stud.* **6** 13–25
Gillson L, Dirk C and Gell P 2021 Using long-term data to inform a decision pathway for restoration of ecosystem resilience *Anthropocene* **36** 100315
Glaser R 2008 Klimageschichte Mitteleuropas: 1200 Jahre Wetter, Klima, Katastrophen Primus Verlag, Darmstadt p 272
Gómez-Baggethun E, Corbera E and Reyes-Garcia V 2013 Traditional ecological knowledge and global environmental change: research findings and policy implications *Ecol. Soc.* **18** 72–79
Gouramanis C, Wilkins D and De Deckker P 2010 6000 years of environmental changes recorded in Blue Lake, South Australia, based on ostracod ecology and valve chemistry *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **297** 223–37
Grocutt H S, Carleton W C, Fenech K, Gauci R, Grima R, Sceri E M L, Stewart M and Vella N 2021 Preprint (https://doi.org/10.31219/osf.io.6m5yh)
Guillet S et al 2017 Climate response to the samalas volcanic eruption in 1257 revealed by proxy records *Nat. Geosci.* **10** 123–8
Gunn J D 2000 *The Years without Summer. Tracing AD 536 and Its Aftermath British Archaeological Reports* (*International Series*) vol 872 (Oxford: Archaeopress)
Gurrapu S, Sauchyn D J and Hodder K R 2022 Assessment of the hydrological drought risk in Calgary, Canada using weekly river flows of the past millennium *J. WaterClim. Change* **13** 1920–35
Guttmann-Bond E B 2010 Sustainability out of the past: how archaeology can save the planet *World Archaeol.* **42** 355–66
Haldon J, Mordechai L, Newfield T, Chase A F, Izdebski A, Guzowski P, Labuhn I and Roberts N 2018 History meets palaeoscience: consilience and collaboration in studying past societal responses to environmental change *Proc. Natl Acad. Sci.* **115** 3210–8
Hall J 2021 Maliseet cultivation and climatic resilience on the Welastekw/St. John River during the Little Ice Age *Acadiensis* **44** 3–25
Harris R M B et al 2018 Biological responses to the press and pulse of climate trends and extreme events *Nat. Clim. Change* **8** 579–87
Hegmon M, Peeples M A, KinZig A P, Kulow S, Meegan C M and Nelson M 2008 Social transformation and its human cost in the Prehispanic U.S. southwest *Am. Anthropol.* **110** 313–24
Hickel J 2018 The contradiction of the sustainable development goals: growth versus ecology on a finite planet *Sustain. Dev.* **27** 873–84
Higgs E, Falk D, Guerrini A, Hall M, Harris J, Hobbs R J, Jackson S T, Rhemtulla J M and Thorp W 2014 The changing role of history in restoration ecology *Front. Ecol. Environ.* **12** 499–506
Hodell D A, Curtis J H and Brenner M 1995 Possible role of climate in the collapse of classic maya civilization *Nature* **375** 391–4
Høilund Nielsen K 2005 "...the sun was darkened by day and the moon by night..there was distress among men...'—on social

and political development in 5th- to 7th-century southern Scandinavia *Studien Sachsenforschung* **15** 247–85
Holling C S and Gunderson L H 2002 Resilience and adaptive cycles *Panarchy: Understanding Transformations in Human and Natural Systems* ed L H Gunderson and C S Holling (Washington: Island Press) ch 2, p 533
Hönisch B *et al* 2012 The geological record of ocean acidification *Science* **335** 1058–63
Hu A, Meehl G A, Han W, Otto-Bliesner B, Abe-Ouchi A and Rosenbloom N 2015 Effects of the bering strait closure on AMOC and global climate under different background climate *Prog. Phys. Oceanogr.* **132** 174–96
Hussain S T and Riede F 2020 Paleoenvironmental humanities: challenges and prospects of writing deep environmental histories *WIREs Clim. Change* **11** e667
Ionita M, Dima M, Nagavciuc V, Scholz P and Lohman G 2021 Past megadroughts in central Europe were longer, more severe and less warm than modern droughts *Commun. Earth Environ.* **2** 61
IPCC 2022 *AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability. The Working Group II Contribution to the Sixth Assessment Report* ed H-O Pörtner *et al* (Cambridge University Press)
IPCC 2021 Summary for policy makers in climate change 2021: the physical science basis *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al* (Cambridge University Press) p 41
Ivarsson L N, Andrèn T, Moros M, Andersen T, Lönn M and Andrèn E 2019 Baltic Sea coastal eutrophication in a thousand year perspective *Front. Environ. Sci.* **7** 88
Janakew K, Atwater B F, Sawai Y, Choowong M, Charoentitirat T, Martin M E and Prendergast A 2008 Medieval forewarning of the 2004 Indian Ocean tsunamis in Thailand *Nature* **455** 1228–31
Jariel K 2021 Climate disaster and the resilience of local maritime networks: two examples from the Aegean Bronze Age *Quat. Int.* **597** 118–30
Kaplan J O, Krumhardt K M, Ellis E C, Ruddiman W F, Lemmen C and Goldewijk K K 2010 Holocene carbon emissions as a result of anthropogenic land cover change *Holocene* **21** 775–91
Keenan B, Imfeld A, Johnston K, Breckenridge A, Gèlinas Y and Douglas P M J 2021 Molecular evidence for human population change associated with climate events in the Maya lowlands *Quat. Sci. Rev.* **258** 106904
Kelman I 2017 Linking disaster risk reduction, climate change, and the sustainable development goals *Disaster Prev. Manage: Int. J.* **26** 254–8
Kerr S, Krogh U and Riede F 2022 Experimental participatory methodology brings local pasts to contemporary climate action *Clim. Action* **1** 5
Kiage L M and Liu K-B 2009 Palynological evidence of climate change and land degradation in the Lake Baringo area, Kenya, east Africa, since AD 1650 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **279** 60–72
Klassen S and Evans D 2020 Top-down and bottom-up water management: a diachronic model of changing water management strategies at Angkor, Cambodia *J. Athropol. Archaeol.* **58** 101166
Kleijne J, Weinelt M and Müller J 2020 Late neolithic and chalcolithic maritime resilience? The 4.2 ka BP event and its implications for environments and societies in northwest Europe *Environ. Res. Lett.* **15** 125003
Klinger Y, Etchebes M, Tapponnier P and Narteau C 2011 Characteristic slip for five 766 great earthquakes along the Fuyun fault in China *Nat. Geosci.* **4** 389–92
Kopp R E, Shwom R, Wagner G and Yuan J 2016 Tipping elements and climate-economic shocks: pathways toward integrated assessment *Earth's Future* **4** 346–72
Lam D, Thompson C, Croke J, Sharma A and Macklin M 2017 Reducing uncertainty with flood frequency analysis: the contribution of paleoflood and historical flood information *Water Resour. Res.* **53** 2312–27
Leng M J and Marshall J D 2004 Palaeoclimate interpretation of stable isotope data from lake sediment archives *Quat. Sci. Rev.* **23** 811–31
Lenton T M, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffan W and Schellnhuber H J 2019 Climate tipping points—too risky to bet against *Nature* **575** 592–8
Lesk C, Rowhani P and Ramankutty N 2016 Influence of extreme weather disasters on global crop production *Nature* **529** 84–87
Li P P 2020 Organizational resilience for a new normal: balancing the paradox of global interdependence *Manage. Organ. Rev.* **16** 503–9
Lim M M L, Jørgenson P and Wyborn C A 2018 Reframing the sustainable development goals to achieve sustainable development in the athropocene—a systems approach *Ecol. Soc.* **23** 22
Löwenborg D 2012 An iron age shock doctrine—did the AD 536–7 event trigger large-scale social changes in the Mälaren valley area? *J. Archaeol. Ancient Hist.* **4** 1–29
Lyon C *et al* 2021 Climate change research and action must look beyond 2100 *Glob. Change Biol.* **28** 349–61
Marsh A, Fleitmann D, Al-Manmi D A M, Altaweel M, Wengrow D and Carter R 2017 Mid- to late-holocene archaeology, environment and climate in the northeast Kurdistan region of Iraq *Holocene* **28** 955–67
Masson-Delmotte V *et al* 2013 Information from paleoclimate archives *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker *et al* (Cambridge: Cambridge University Press)
McCarroll D and Loader N J 2004 Stable isotopes in tree rings *Quat. Sci. Rev.* **23** 771–801
McCorriston J and Field J 2020 *Anthropocene: A New Introduction to World Prehistory* (London: Thames & Hudson)
Meese D A *et al* 1994 The accumulation record from the GISP2 core as an indicator of climate change throughout the holocene *Science* **266** 1680–2
Menton M, Larrea C, Latorre S, Martinez-Alier J, Peck M, Temper L and Walter M 2020 Environmental justice and the SDGs: from synergies to gaps and contradictions *Sustain. Sci.* **15** 1621–36
Mills K *et al* 2017 Deciphering long-term records of natural variability and human impact as recorded in lake sediments: a palaeolimnological puzzle *Wiley Interdiscip. Rev.: Water* **4** e1195
Mills K and Jones M 2021 Palaeoscience and the UN sustainable development goals *Pages Horiz.* **1** 4–5
Mischke S, Zhang C, Liu C, Zhang J, Lai Z and Long H 2019 Landscape response to climate and human impact in western China during the Han dynasty *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H-R Bork, X Fang and S Mischke (Cham: Springer Nature) ch 13, p 506
Mooney S D *et al* 2011 Late quaternary fire regimes of Australasia *Quat. Sci. Rev.* **30** 28–46
Morales M *et al* 2020 Six hundred years of South American tree rings reveals an increase in severe hydroclimatic events since mid-20th century *Proc. Natl Acad. Sci.* **117** 16816–23
Morrill C 2004 The influence of Asian summer monsoon variability on the water balance of a Tibetan lake *J. Paleolimnol.* **32** 273–86
Mostert E 2012 Water management on the island of IJsselmonde 1000–1953: polycentric governance, adaptation and petrification *Ecol. Soc.* **17** 12
Nelson M *et al* 2016 Climate challenges, vulnerabilities, and food security *Proc. Natl Acad. Sci.* **113** 289–303
Nunn P D, Hunter-Anderson R, Carson M T, Thomas F, Ulm S and Rowland M J 2007 Times of plenty, times of less: last millennium societal disruption in the Pacific Basin *Hum. Ecol.* **35** 385–401

O'Brien K, Eriksen S, Nygaard L P and Schjolden A 2007 Why different interpretations of vulnerability matter in climate change discourses *Clim. Policy* **7** 73–88
O'Donnell A J, McCaw W L, Cook E R and Grierson P F 2021 Megadroughts and pluvials in southwest Australia: 1350–2017CE *Clim. Dyn.* **57** 1817–31
Opel T, Meyer H, Wetterich S, Laepple T, Dereviagin A and Murton J 2018 Ice wedges as archives of winter paleoclimate: a review *Permafr. Periglac. Process.* **29** 199–209
PAGES2k Consortium 2012 Continental-scale temperature variability during the past two millennia *Nat. Geosci.* **6** 339–46
Palmer J G, Cook E R, Turney C S M, Allen K, Fenwick P, Cook B I, O'Donnell A, Lough J M, Grierson P and Baker P 2015 Drought variability in the eastern Australia and New Zealand summer drought atlas (ANZDA, CE 1500–2012) modulated by the interdecadal Pacific Oscillation *Environ. Res. Lett.* **10** 124002
Panyushkina I R, Macklin M G, Toonen W H J and Meko D M M 2019 Water supply and ancient society in the Lake Balkhash Basin: runoff variability along the historical silk road *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H-R Bork, X Fang and S Mischke (Cham: Springer Nature) ch 18, p 506
Pearce T, Ford J, Cunsolo A and Smit B 2015 Inuit traditional ecological knowledge (TEK), subsistence hunting and adaptation to climate change in the Canadian Arctic *Arctic* **68** 233–45
Peel M C, MacMahon T A and Finlayson B L 2004 Continental differences in the variability of annual runoff-update and reassessment *J. Hydrol.* **295** 185–97
Penny D, Zachreson C, Fletcher R, Lau D, Lizier J T, Fischer N, Evans D, Pottier C and Prokopenko M 2018 The demise of Angkor: systemic vulnerability of urban infrastructure to climatic variations *Sci. Adv.* **4** eaau4029
Peregrine P N 2018 Social resilience to climate-related disasters in ancient societies: a test of two hypotheses *Weather Clim. Soc.* **10** 145–61
Peregrine P N 2020 Climate and social change at the start of the Late Antique Little Ice Age *Holocene* **30** 1643–8
Peregrine P N 2021 Social resilience to nuclear winter: lessons from the late Antique Little Ice Age *Glob. Secur.: Health Sci. Policy* **6** 57–67
Peros M C, Munoz S, Gajewski K and Viau A E 2010 Prehistoric demography of North Africa inferred from radiocarbon data *J. Archaeol. Sci.* **37** 656–64
Peterson T C *et al* 2013 Monitoring and understanding changes in heat waves, col waves, floods and droughts in the United States: state of knowledge *Bull. Am. Meteorol. Soc.* **94** 821–34
Petraglia M D, Grocutt H S, Guagnin M, Breeze P S and Boivin N 2020 Human responses to climate and ecosystem changes in ancient Arabia *Proc. Natl Acad. Sci.* **117** 8263–70
Petzold J, Andrews N, Ford J D, Hedemann C and Postigo J C 2020 Indigenous knowledge on climate change adaptation: a global evidence map of academic literature *Environ. Res. Lett.* **15** 113007
Pfister C 2009 The "disaster gap" of the 20th Century and the loss of traditional disaster memory GAIA *Ecol. Perspect. Sci. Soc.* **18** 239–46
Phillips D H, Reinink Y, Skapura T E, Ester C E and Skindlov J A 2009 Water resources planning and management at the Salt River project, Arizona, USA *Irrig. Drain. Syst.* **23** 109
Porter T J, Froese D G, Feakins S J, Bindeman I N, Mahony M E, Pautler B G, Reichart G-J, Sanborn P T, Simpson M J and Weijers J W H 2016 Multiple water isotope proxy reconstruction of extremely low last glacial temperatures in Eastern Beringia (Western Arctic) *Quat. Sci. Rev.* **137** 113–25
Power S, Casey T, Folland C, Colman A and Mehta V 1999 Inter-decadal modulation of the impact of ENSO on Australia *Clim. Dyn.* **15** 319–24
Price and Graslund 2015 Excavating the fimbulwinter? Archaeology, geomythology and the climate event(s) of AD536 *Past Vulnerability: Volcanic Eruptions and Human Vulnerability in Traditional Societies past and Present* ed F Reide (Aarhus: Arahus University Press) ch 6, pp 109–32
Quiggan D, De Meyer K, Hubble-Rose L and Froggatt A 2021 *Climate Change Risk Assessment: Summary of Research Findings* (London: Chatham House, The Royal Institute of International Affairs) p 16
Ramankutty N, Foley J A, Norman J and McSweeney K 2002 The global distribution of cultivable lands: current patterns and sensitivity to possible climate change *Glob. Ecol. Biogeogr.* **11** 377–92
Ran M and Chen L 2019 The 4.2ka BP events and its cultural responses *Quat. Int.* **521** 158–67
Redman C 2012 Global environmental change, resilience, and sustainable outcomes *Surviving Sudden Environmental Change* ed J Cooper and P Sheets (University Press of Colorado) pp 237–44
Rees M 2017 Museums as catalysts for change *Nat. Clim. Change* **7** 166
Reichstein M, Reide F and Frank D 2021 More floods, fires and cyclones—plan for domino effects on sustainability goals *Nature* **592** 347–9
Reilly J and Schimmelpfennig D 2000 Irreversibility, uncertainty, and learning: portraits of adaptation to long-term climate change *Clim. Change* **45** 253–78
Riede F 2022 Deep history curricula under the mandate of the anthropocene. Insights from interdisciplinary shadow places *FECUN* **1** 172–85
Riris P and Arroyo-Kalin M 2019 Widespread population decline in South America correlates with mid-Holocene climate change *Sci. Rep.* **9** 6850
Rockstrom J *et al* 2009 Planetary boundaries: exploring the safe operating space for humanity *Ecology and Society* **14** 32
Rogers J D, Nichols T, Emmerich T, Latek M and Cioffi-Revilla C 2012 Modelling scale and variability in human-environmental interactions in Inner Asia *Ecol. Modelling* **241** 5–14
Rolett B and Diamond J 2004 Environmental predictors of pre-European deforestation on Pacific islands *Nature* **431** 443–6
Romanello M *et al* 2021 The 2021 report of the lancet countdown on health and climate change: code red for a healthy future *Lancet* **398** 1619–62
Rose N L 2015 Spheroidal carbonaceous fly ash particles provide a globally synchronous stratigraphic marker for the Anthropocene *Environ. Sci. Technol.* **49** 4155–62
Ruddiman W F 2003 The anthropogenic greenhouse Era began thousands of years ago *Clim. Change* **61** 261–93
Sachs J D, Kroll C K, Lafortune G, Fuller G and Woelm F 2021 *Sustainable Development Report 2021: The Decade of Action for the Sustainable Development Goals* (Cambridge: Cambridge University Press) p 518
Sachs J D, Schmidt-Traub G, Mazzucato M, Messner D, Nakicenovic N and Rockström J 2019 Six transformations to achieve the sustainable development goals *Nat. Sustain.* **2** 805–14
Sadler J, Webb G E, Nothdurft L D and Dechnik B 2014 Geochemistry-based coral palaeoclimate studies and the potential of 'non-traditional' (non-massive Porites) corals: recent developments and future progression *Earth-Sci. Rev.* **139** 291–316
Sadowski R F 2020 The influence of cultural factors on the collapse of the Greenland norse civilization *Studia Ecologiae Bioethicae* **18** 217–33
Sandweiss D H and Kelley A R 2012 Archaeological contributions to climate change research: the archaeological record as a paleoclimatic and paleoenvironmental archive *Annu. Rev. Anthropol.* **41** 371–91
Saunders K M, Roberts S J, Perren B, Butz C, Ime L, Davies S, Nieuwenhuyze W V, Grosjean M and Hodgson D A 2018

Holocene dynamics of the Southern westerly winds and possible links to CO2 outgassing *Nat. Geosci.* **11** 650–5

Scanlon J 1988 Winners and losers: some thoughts about the political economy of disaster *Int. J. Mass Emerg. Disasters* **6** 47–63

Scheffer M, van Nes E H, Bird D, Bocinsky R K and Kohler T A 2021 Loss of resilience preceded transformations of pre-Hispanic Pueblo societies *Proc. Natl Acad. Sci.* **118** e2024397118

Schneider L, Smerdon J E, Büntgen U, Wilson R J S, Myglan V S, Kirdyanov A V and Esper J 2015 Revising midlatitude summer temperatures back to A.D. 600 based on a wood density network *Geophys. Res. Lett.* **42** 4556–62

Seara D A *et al* 2020 Human settlement of East Polynesia earlier, incremental, and coincident with prolonged South Pacific drought *Proc. Natl Acad. Sci.* **117** 8813–9

Sheets P 2020 Do disasters always enhance inequality? *Going Forward by Looking Back: Archaeological Perspectives on Socio-Ecological Crisis, Response, and Collapse* ed F Reide (New York: Berghahn Books) pp 135–81

Skene K R 2021 No goal is an island: the implications of systems theory for the sustainable development goals *Environ. Dev. Sustain.* **23** 9993–10012

Smith A D, Kaminski M J, Kanda K, Sweet A D, Betancourt J L, Holmgren C A, Hempel E, Alberti F and Hofreiter M 2021 Recovery and analysis of ancient beetle DNA from subfossil packrat middens using high-throughput sequencing *Sci. Rep.* **11** 12635

Smith J B, Hallett K, Henderson J and Strzepek K M 2007 Expanding the tool kit for water management in an uncertain climate *Southwest Hydrol.* **2007**

Smol J P, Birks H J and Last W M (eds) 2001a *Tracking Environmental Change Using Lake Sediments Volume 3: Terrestrial, Algal, and Siliceous Indicators* (Dordrecht: Kluwer Academic Publishers) p 371

Smol J P, Birks H J and Last W M (eds) 2001b *Tracking Environmental Change Using Lake Sediments Volume 4: Zoological Indicators* (Dordrecht: Kluwer Academic Publishers) p 217

Spate M 2019 Reconsidering archaeological and environmental proxies for long term human-environment interactions in the Valley of Kashmir *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H-R Bork, X Fang and S Mischke (Cham: Springer Nature) ch 6, p 506

St George S, Hefner A M and Avila J 2020 Paleofloods stage a comeback *Nat. Geosci.* **13** 766–8

Stahle D W *et al* 2016 The Mexican drought atlas: tree-ring reconstructions of the soil moisture balance during the late pre-Hispanic, colonial and modern eras *Quat. Sci. Rev.* **149** 34–60

Staubwasser M and Weiss H 2006 Holocene climate and cultural evolution in late prehistoric-early historic west Asia *Quat. Res.* **66** 372–86

Steffen W *et al* 2018 Trajectories of the Earth system in the athropocene *Proc. Natl Acad. Sci.* **115** 8252–9

Steiger N J, Smerdon J E, Cook E R and Cook B I 2018 A reconstruction of global hydroclimate and dynamical variables over the common Era *Sci. Data* **5** 180086

Stephens L *et al* 2019 Archaeological assessment reveals Earth's early transformation through land use *Science* **365** 897

Stewart I S and Gill J C 2020 Social geology—integrating sustainability concepts into Earth sciences *Proc. Geol. Assoc.* **128** 165–72

Stoffel M *et al* 2022 Climate, weather and socio-economic conditions corresponding with the mid-17th century volcanic eruption cluster *Clim. Past* In press (available at: https://cp.copernicus.org/preprints/cp-2021-148/cp-2021-148.pdf)

Szczesny T J 2016 Was the 4.2 ka event an anthropogenic disaster? *Open J. Ecol.* **6** 613–31

Thiery W *et al* 2021 Intergenerational inequities in exposure to climate extremes *Science* **374** 158–60

Torrence R 2020 Collapse, resilience, and adaptation, *Going Forward by Looking Back: Archaeological Perspectives on Socio-Ecological Crisis, Response, and Collapse* ed F Reide and P Sheets (Berghahn Books) ch 5, p 705

Tvauri A 2014 The impact of the climate catastrophe of 536–537 AD in Estonia and neighbouring areas *Est. J. Archaeol.* **18** 30–56

United Nations 2015a Resolution adopted by the general assembly on 25 September 2015

United Nations 2015b Sendai framework for disaster risk reduction 2015–2030 p 32 (available at: www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf)

United Nations 2020 *Sustainable Development Outlook 2020. Achieving the SDGs in the Wake of COVID-19: Scenarios for Policymakers* (United Nations Department of Economic and Social Affairs) p 57

Van Denter H 2021 Monitoring changes in South Africa's surface water extent fir reporting sustainable development goal sub-indicator 6.6.1.a *S. Afr. J. Sci.* **117** 8806

Waldinger M 2015 the economic effects of long-term climate change: evidence from the little ice age *Centre for Climate Change Economics and Policy Working Paper No. 239, Grantham Research Institute on Climate Change and the Environment, Working Paper No. 214* p 46

Walker B, Holling C S, Carpenter S R and Kinzig A 2004 Resilience, adaptability and transformability in social-ecological systems *Ecol. Soc.* **9** 5

Walker M J C, Berkelhammer M, Björck S, Cwynar L C, Fisher D A, Long A J, Lowe J J, Newnham R M, Rasmussen S O and Weiss H 2012 Formal subdivision of the Holocene Series/Epoch: a discussion paper by a working group of INTIMATE (integration of ice-core, marine and terrestrial records) and the subcommission on quaternary stratigraphy (International Commission on Stratigraphy) *J. Quat. Sci.* **27** 649–59

Wang J, Sun L, Chen L, Xu L, Wang Y and Wang X 2016 The abrupt climate change near 4,400 yr BP on the cultural transition in Yuchisi, China and its global linkage *Sci. Rep.* **6** 27723

Wang R, Dearing J A, Langdon P G, Zhang E, Yang X, Dakos V and Scheffer M 2012 Flickering gives early warning signals of a critical transition to a eutrophic lake state *Nature* **492** 419–22

Warden L *et al* 2017 Climate induced human demographic and cultural change during the mid-Holocene *Sci. Rep.* **7** 15251

Weiberg E and Finnè M 2018 Resilience and persistence of ancient societies in the face of climate change: a case study from late Bronze Age Peloponnese *World Archaeol.* **50** 584–602

Weiss H, Courty M A, Wetterstrom W, Guichard F, Senior L, Meadow R and Curnow A 1993 The genesis and collapse of third millennium North mesopotamian civilization *Science* **261** 995–1004

Westerhold T *et al* 2021 An astronomically dated record of Earth's climate and its predictability over the last 66 million years *Science* **369** 1383–7

Wilhelm B *et al* 2013 Palaeoflood activity and climate change over the last 1400 years recorded by lake sediments in the north-west European Alps *J. Quat. Sci.* **28** 189–99

Wilhelm B *et al* 2019 Interpreting historical, botanical, and geological evidence to aid preparations for future floods *Wiley Interdiscip. Rev.: Water* e1318

Williams A P, Cook B I and Smerdon J E 2022 Rapid intensification of the emerging southwestern North American megadrought in 2020–2021 *Nat. Clim. Change* **12** 232–4

Williams J W, Blois J L and Shuman B N 2011 Extrinsic and intrinsic forcing of abrupt ecological change: case studies from the late quaternary *J. Ecol.* **99** 664–77

Willis K J and Bhagwat S 2009 Biodiversity and climate change *Science* **326** 806–7

Willis K J, Sümegi P, Raun M, Bennett K D and Tòth A 2015 Prehistoric land degradation in Hungary: who, how and why? *Antiquity* **72** 101–13

Wilson S, Pearson L J, Kashima Y, Lusher D and Pearson C 2013 Separating adaptive maintenance (resilience) and transformative capacity of social-ecological systems *Ecol. Soc.* **18** 22

Wingard G L, Bernhardt C E and Wachnicka A H 2017 The role of paleoecology in restoration and resource management—the past as a guide to future decision-making: review and example from the greater everglades ecosystem, USA *Front. Ecol. Evol.* **5** 11

Xu C, Kohler T A, Lenton T M, Svenning J-C and Scheffer M 2020 Future of the human climate niche *Proc. Natl Acad. Sci.* **117** 11350–5

Yang E Y, Bork H-R, Fang X, Mischke S, Weinelt M and Wisehöfer J 2019 On the paleo-climatic/environmental impacts and socio-cultural system resilience along the silk road *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H-R Bork, X Fang and S Mischke (Cham: Springer Nature) ch 1, p 506

Yang E Y, Chen J, Geng J, Fang Y and Yang W 2021 Social resilience and its scale effects along the historical Tea-Horse Road *Environ. Res. Lett.* **16** 045001

Zennaro P *et al* 2014 Fire in ice: two millennia of boreal forest fire history from the Greenland NEEM ice core *Clim. Past* **10** 1905–24