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

K J Allen[1,2,3,*], F Reide[4], C Gouramanis[5], B Keenan[6], M Stoffel[7,8,9], A Hu[10] and M Ionita[11,12]

1 School of Geography, Planning, and Spatial Sciences, University of Tasmania, Churchill Avenue, Sandy Bay 7005, Australia
2 School of Ecosystem and Forest Sciences, University of Melbourne, 500 Yarra Boulevard, Richmond 3121, Australia
3 ARC Centre of Excellence for Biodiversity and Heritage, University of New South Wales, Sydney 2052, Australia
4 Department of Archaeology and Heritage Studies, Aarhus University, Moesgård Allé 20, Højbjerg 8270, Denmark
5 Research School of Earth Sciences, The Australian National University, Australian Capital Territory, Canberra 0200, Australia
6 Department of Earth and Planetary Sciences, McGill University, Montréal, QC H3A 0E8, Canada
7 Climate Change Impacts and Risks in the Anthropocene (C-CIA), Institute for Environmental Sciences, University of Geneva, 66 Boulevard Carl-Vogt, Geneva 1205, Switzerland
8 Department of Earth Sciences, University of Geneva, 13 rue des Maraîchers, Geneva 1205, Switzerland
9 Department F.A. Forel for Environmental and Aquatic Research, University of Geneva, 66 Boulevard Carl-Vogt, Geneva 1205, Switzerland
10 National Center for Atmospheric Research, 850 Table Mesa Drive, Boulder, CO 80305, United States of America
11 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven 27570, Germany
12 Emil Racovita Institute of Speleology, Romanian Academy, Cluj-Napoca 400006, Romania
* Author to whom any correspondence should be addressed.

E-mail: Kathryn.Allen@utas.edu.au

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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).

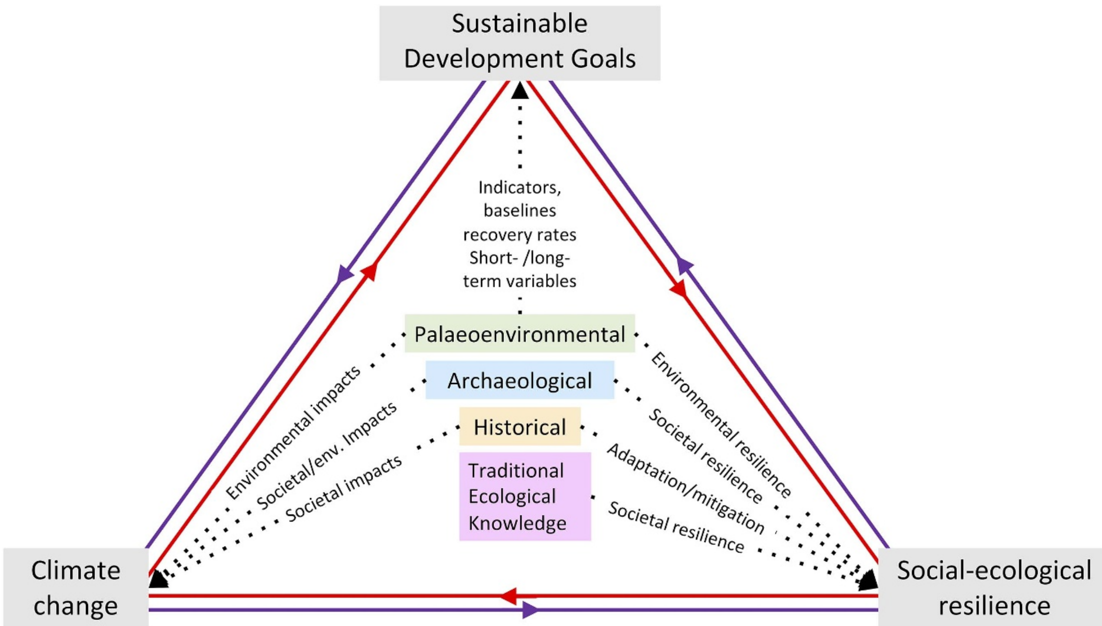

Figure 1. Simplified positive feedback loop between the sustainable development goals framework, social-ecological resilience and climate change. Contributions of historical, archaeological and paleo-data are central to understanding past environmental change, including responses to climate change and 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)

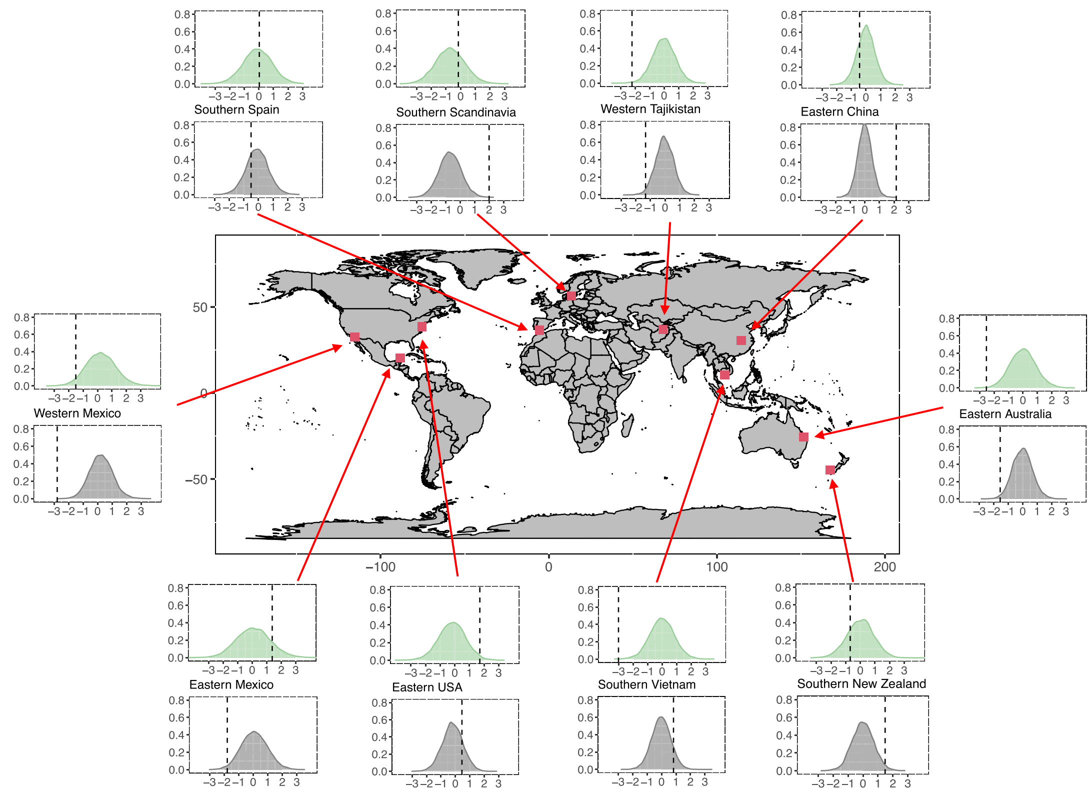

Figure 2. Comparison of average hydroclimate conditions over the 2000–2004 and 2016–18 baselines relevant for Target 6.6 (By 2020, protect and restore water-related ecosystems') with distributions of 10 000 five- and three year mean hydroclimate for 3° × 3° areas around selected RAMSAR-listed wetlands (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,

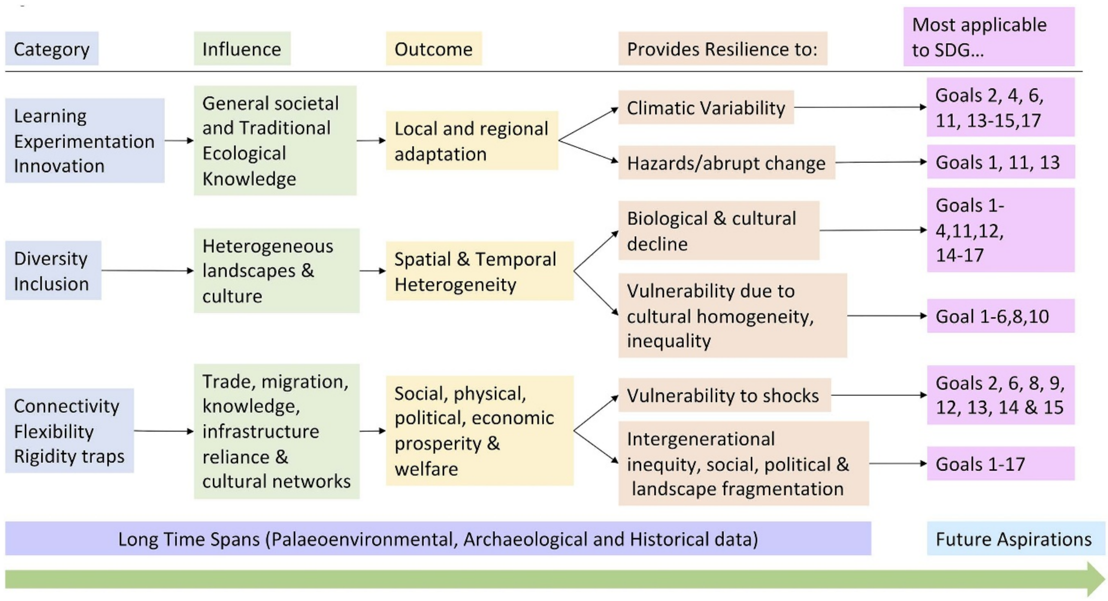

Figure 3. Schematic showing pathways by which information in historical and archaeological records—as categorised in the manuscript—become relevant to the SDGs.

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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ORCID iDs

K J Allen https://orcid.org/0000-0002-8403-4552
F Reide https://orcid.org/0000-0002-4879-7157
C Gouramanis https://orcid.org/0000-0003-2867-2258
B Keenan https://orcid.org/0000-0002-0274-8878
M Stoffel https://orcid.org/0000-0003-0816-1303
A Hu https://orcid.org/0000-0002-1337-287X
M Ionita https://orcid.org/0000-0001-8240-4380

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