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Paleo-data is policy relevant: How do we better incorporate it in policy and decision making?

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ABSTRACT

The relatively recent acceleration of human activities that adversely impact Earth's systems has led to an increasingly urgent impetus to understand, mitigate, and adapt to these impacts. However, comprehension of natural systems, and fluctuations in their state, requires long-term data to capture the magnitude and direction of changes in these systems over very long time frames (decades to millennia). The current reliance on short instrumental or monitoring time series, that span only the last century or less, is simply inadequate to sustainably manage natural systems. Despite this growing need for long-term information and the abundance of paleo-data available, there has been little effort or success in incorporating paleo-science into policy and decision making. We use examples to demonstrate how paleo-data provides important insights into problems from three different domains: forest management and restoration, water resource management and wetland ecosystem management. We discuss a process through which opportunities to better utilise paleo-data by policy decision makers to achieve better policy outcomes can be identified. This involves first acknowledging the very different characteristics of paleo-scientists and policy makers, followed by recognition of the constraints, or barriers to the uptake of paleo-science information. These barriers exist as much for scientists as for policy makers. Identification of barriers enables opportunities for enhanced collaboration to improve the use of paleo-data for policy and decision making to be identified. Fundamentally, much greater interaction between paleo-scientists and policy makers is required to promote better science translation, data availability as well as to promote scientific literacy in government and industry, and policy literacy in the paleo-science community. Processes such as co-design are one way to achieve these aims, but require adequate resourcing, time and the collective will to collaborate.

1. Introduction

The perceived increase of environmental disasters in recent decades (Alimonti and Mariani, 2024) and the increasing financial cost associated with major events (Boccard, 2021; Coronese et al., 2019), underlie renewed emphasis on understanding and/or adapting to these events into the future. Additionally, anthropogenic climate change is expected to exacerbate the impact, severity and frequency of these environmental disasters. Environmental disasters include both slow-onset, long duration hazards (e.g. sea level change, pollution) and rapid onset, short duration hazards (e.g. fires, heatwaves, landslides, cyclones or hurricanes, floods and drought (Field et al., 2012; Seneviratne et al., 2021). As a result, there is increasing pressure for governments to invest in work to reduce the impacts of disasters or prepare communities through adaptation, and many are doing so (Paunga and Lassa, 2020; Lassa et al., 2019; Ishiwatari and Surjan, 2019). This requires, however, an adequate level of information about the relevant systems.

Over the past few decades, high-level responses to the threat of environmental disaster occurrence have included the development of a number of large-scale and internationally coordinated responses or frameworks. The United Nations Framework Convention on Climate Change (UNFCCC), the Sendai Framework for Disaster Risk Reduction, the Sustainable Development Goals, Convention of Wetlands, the Intergovernmental Panel on Biodiversity and Ecosystem Services are just a few of these that either have large-scale or even global coverage (Table 1). The various international frameworks and conventions have a

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central focus on sustainable development, and provide high-level direction to assess environmental and climate change at global to local scales, and to identify and promote practical and pragmatic solutions. Each of these frameworks and conventions considers interlinkages between Earth's systems and processes and humanity's requirements with a future-centric perspective. These frameworks and conventions provide national and subnational governments, industry, and communities with guidance and/or strategies to better assess how risk, vulnerability and/or exposure has changed over a specified time frame. The conventions and frameworks attempt to promote economically, politically, socially and scientifically sound guidance to benefit societies and the environments they rely on. Many governments and organizations have responded to these conventions by developing a suite of monitoring tools and processes to provide key information to support decision making and help to inform current and future risk. For example, the realization that anthropogenic climate change is increasing the risk of local and global systemic changes that may be irreversible (i.e. tipping points) has driven the need for national and subnational climate risk assessments and adaptation plans. The decision at the UNFCCC's 28th Conference of the Parties (COP28) for all countries to have adaptation plans in place by 2030 reinforces the urgency required to act.

However, despite an increased emphasis on monitoring recent change, the desire to understand future risk and the need to adapt to impending environmental change, the roles of natural variability over long frames or occurrence of past catastrophic events have often been downplayed, presented erroneously (Esper et al., 2024), or, in many cases, ignored. Yet, this information can be vital for the assessment of hazards and threats. Many of the existing international frameworks or conventions do not refer to paleo-data (e.g. only four of 11 listed in Table 1 mention paleo-data). This is despite the considerable value of such data, and the requirement for long-term data to adequately evaluate risk (Harle et al., 2005; Velez et al., 2018; Fordham et al., 2020; Allen et al., 2020). The lack of emphasis on considering data and information sources derived over long time-frames that extend beyond the satellite or instrumental monitoring era in policy and management settings is a critical oversight as many natural processes evolve or vary over time frames much longer than the instrumental record (Walker et al., 2012). This can lead to incorrect conclusions about, for example, the length and persistence of dry spells that are possible (Kröpelin et al., 2008), or the height of previous sea levels (Meltzner et al., 2017) and the concomitant position of coastlines under natural conditions.

Three examples that illustrate the kinds of issue that may arise when guidelines based on 'short-term' data are used include Australia's Murray-Darling Basin (Gillson and Marchant, 2014), the Colorado River Compact of 1922 (Meko et al., 2022), and the baseline used to assess progress towards Target 6.6 of the SDG framework (By 2020, protect and restore water-related ecosystems; as measured by spatial extent of wetland systems). In the case of the Murray Darling, the use of a 1985 salinity baseline against which to measure wetland health proved disastrous because the baseline did not represent appropriate natural conditions for that system. Instead, the baseline represented a system in a severe state of degradation due to long-term impacts of use since European arrival. Similarly, reliance on a short and particularly wet period for planning resulted in the misallocation of water in the Colorado Basin (Meko et al., 2022). These 1922 allocations to Basin states provoked many questions as drought conditions of the 1950s and 1960s set in, along with increased water use. The later paleo-flow reconstructions demonstrated the need to consider a much longer period when developing allocation plans. Allen et al. (2022) demonstrate the folly of attempting to apply universal baselines predicated on short-term data that do not consider spatial and temporal variability in the impacts of natural processes. In that study, the authors used tree-ring drought reconstructions to demonstrate that the use of a universal and modern short-term baseline for assessment of improvements in wetland condition was flawed. Fig. 1 shows a comparison of hydroclimate conditions over the defined 5-year baseline period (2000–2004) with a probability distribution based on 10,000 5-year periods randomly sampled from the drought reconstruction for regions around two Wetlands of International Importance in New Zealand and Tajikistan. Clearly, for the two selected wetlands shown here, the baseline does not represent either 'average' conditions or the range of possible conditions, indicating that assessments of progress against SDG Target 6.6 are likely of little meaning or value (for more detail see Allen et al., 2022).

Paleo-data has provided invaluable insights into natural cycles/variability over relatively short (decadal) to long (millions of years) time scales, into abrupt changes in climate as well as into the occurrence and impact of, and recovery from, hazardous events (e.g., McGuire et al., 2023). Paleo-climate data continues to be vitally important for improving and constraining climate models (Schmidt, 2010; Haywood et al., 2019; Tierney et al., 2020), and for assessing climate sensitivity to increases in CO_2 (Sherwood et al., 2020). However, the greatly increased focus on climate modelling and model outputs over the past three decades has effectively decreased the emphasis placed on paleo-data. This is despite the fact that much of the uncertainty in climate projections relates to natural variability (Barrow and Sauchyn, 2019) and global and local tipping points (Lenton et al., 2023), concepts to which paleo-data

Table 1
Selected examples of major international frameworks, conventions, assessments or intergovernmental bodies in which paleo-data could or has provided useful input.

Framework/convention & establishment date	Purpose	Coverage	Is paleo-information explicitly mentioned?	How paleo-information could be useful
Sendai Framework for Disaster Risk Reduction 2015	Prevent and reduce disaster risk	2015–2030; global	No	Better contextualise risk information
Sustainable Development Goals (SDGs) 2015	Improve sustainability	2015–2030; global	No	Realistic baselines for some targets/indicators
Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) 2012	Strengthen science-policy decision for long term sustainability	ongoing; global	Yes	Long-term baselines and variability
The Convention on Wetlands (Ramsar Convention) est. 1971	Conservation and wise use of wetlands	ongoing; global	No	Long-term baseline and variability
UN Framework on Climate Change (UNFCC) 1994	Prevent 'dangerous' human interference with climate	ongoing; global	Yes	Long-term baselines
Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) 1982	Conserve Antarctic marine life	Antarctic ecosystems	No	Long term variability in ecosystems
Intergovernmental Panel on Climate Change (IPCC) 1988	Assess science of climate change	global; ongoing	Yes	Background context
Convention on Biological Diversity 1992	Promotes nature and human well-being	global; ongoing	No	Background variability/long-term baselines
United Nations Convention to Combat Desertification 2013	Promote practice that avoid, reduce, reverse land degradation (SDG 15)	global; ongoing	Yes	Long-term variability
Minamata Convention on Mercury 2013	Protect human health and environment from anthropogenic Hg	global; ongoing	No	Natural concentrations prior to industrialisation

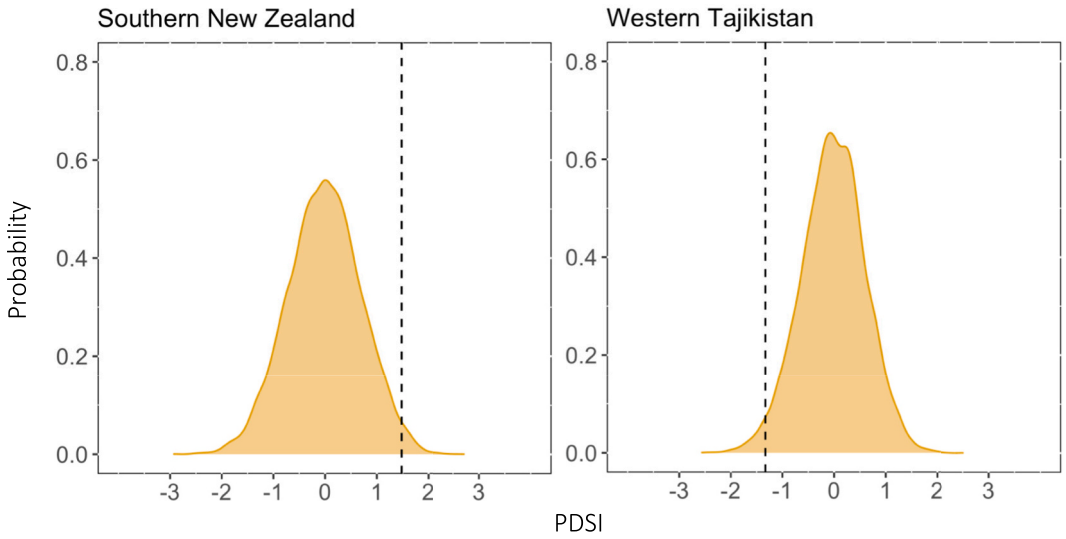

Fig. 1. Comparison of the 2000–2004 baseline hydroclimate conditions (dashed vertical lines) for two Wetlands of International Importance in different regions with the range of possible conditions. The wetlands are in southern New Zealand and Tajikistan, two of teh cases considered in Allen et al. (2022) The range of possible conditions in each case is based on probability distributions derived from 10,000 5-year sets of resampled data from the tree-ring drought atlases over their common period of 1400–2000 for the 3 × 3° around each wetland. The two tree-ring drought atlases used to derive the probability distributions for the respective areas were the Monsoon Asia Drought Atlas and the Australia New Zealand Drought Atlas (Cook et al., 2010; Palmer et al., 2015). See Allen et al. (2022) for more detail.

have contributed significant knowledge. Additionally, the public often appreciate the greater tangibility of change 'observed through' paleo records more than the presentation of model outputs that can differ widely across models.

Many individual paleo-records reflect local-regional environmental characteristics, and this scale of information is critical to the management of local and regional resources and development of guidelines, targets, processes or adaptive measures that are appropriate and place-relevant. Additionally, the assimilation of individual paleo-records into regional atlases and databases can provide profound spatial coverage that individual records lack (e.g., various drought atlases such as Cook et al., 2007, 2010; Stahle et al., 2016). Acting in a vacuum of local long-term information will likely lead to sub-optimal outcomes that fail to meet the objectives and goals of internationally coordinated responses to major problems like climate change. Consider, for example, how to best build adequate management responses to mass coral bleaching and mortality events (Hughes et al., 2018).

Ultimately, information from many sources, including paleo-data is crucial when considering what natural variability and a safe operating space for humanity within planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) really looks like. Here, we briefly explore how paleo-records derived from a variety of sources have the ability to inform policy in an array of local, national and international climate, environment and hazard assessments. We use examples from three different areas including the water industry, forest management and wetland conservation. These three examples enable us to highlight various barriers and enablers to the take-up of paleo-data in policy and management, a starting point to fostering deeper collaboration and engagement between government, industry and paleo-scientists to ensure better resource management and planning outcomes for humanity and the environment. Although very long records that inform us about environmental history over hundreds of thousand or even millions of years (e.g. ice cores, some sediment records) are also extremely valuable, we limit ourselves to discussing how generally higher resolution but temporally shorter paleo-records can inform resource management issues for which contemporary policy decisions can have impacts on much shorter (decadal - millennial) time scales.

2. Examples of management-relevant contributions by paleo-data

2.1. Forest management and restoration

Forests host an abundance of biodiversity and support diverse ecosystem services, store and sequester vast carbon reserves, improve human health and well-being and provide construction materials. They are also places with important cultural and heritage values. Increasing conversion of forests for agricultural purposes or to open parklands as well as growing utilisation of forest resources means forest management is an ongoing and widespread issue. Understanding how forests have changed over millennia and how indigenous peoples have changed the landscape (Adeleye et al., 2021) can help inform current forest management and policy. Paleo-data, such as pollen and plant macrofossils from marine and terrestrial sources and genetic analyses, have contributed to reshaping previous understanding of tree migration routes, understanding that species extinctions have often coincided with increased climate volatility and that oceanic seed dispersal in the tropics over long time frames has played a critical role in tree colonization (Petit et al., 2008). As an ever evolving field, paleoecology contributes increasingly nuanced and valuable insights into forest systems and their function, cultural landscapes, and ultimately, their management. Some key paleo-data contributions regarding forest management or restoration are briefly outlined below.

2.1.1. Fire

Very long-term fire records can be derived from the sedimentary archive (Mooney et al., 2011), with shorter records available in the ice core (Rubino et al., 2016; Zennaro et al., 2014), speleothem (McDonough et al., 2022) and tree-ring archives (Swetnam et al., 2009; Legrand et al., 2016). Charcoal preserved in wetland and marine sediment cores, speleothem and ice-cores provide direct evidence of local or regional fire while pollen data can show vegetation changes in response to specific fire events or fire regime changes over millennia (Carcaillet et al., 2009; Whitlock et al., 2010). Tree-ring fire-scar records can stretch over several centuries (Mundo et al., 2017) and reveal changes in temporal and spatial variability of fire frequency and intensity (Şahan et al., 2023). Fire-scar records in trees and charcol in sediment have also revealed long term climate modulation of fire regimes (Holz et al., 2017;

Mariani and Fletcher, 2016; Calder et al., 2015) and when changes in forest composition have overriden the influence of climate (Gavin et al., 2007). Fire scar records in trees have also been used to reveal how changes in policy can have unintended consequences. Tenzin et al. (2024) and Nguyen et al. (2023) both show how fires have become more widespread in response to policy changes and how such changes interact with major climate modes like ENSO to modulate fire regimes. In Bhutan, the introduction of the *Forest Act 1969* restricted a range of activities in forests, including lighting fires, collecting fuelwood and timber harvesting. In a fuel-limited system, this effectively resulted in an increase in available fuel and greater landscape connectivity, and hence broader-scale fires (Fig. 2). In contrast, resettlement policies in Vietnam that began in the 1960s resulted in the migration of people from urban to regional areas, dramatically increased ignition sources while decreasing the typical return interval of fire (Fig. 2). These sorts of change also have implications for forest dynamics and composition (Nguyen et al., 2023).

In combination with forest dynamics studies (see below), paleoecological fire data provides a backdrop against which to compare 20th-21st century fire regimes and vegetative responses. These responses provide insights into what fire regime would be required to maintain or modify a forested landscape as desired (Long, 2009; Fulé et al., 2003; Cyr et al., 2012; Williams and Baker, 2013; Radcliffe et al., 2024), identify vulnerable landscapes, or fire regimes required for species refugia. They can also be used as vital inputs into models for the prediction of landscape-scale impacts of fire (Gavin et al., 2007). Numerous examples also demonstrate the role of Indigenous peoples in shaping their landscapes using fire and how this has changed with European invasion (Fletcher et al., 2021; Copes-Gerbitz et al., 2023). In providing a range of recommendations for living better with fire, Stephens et al. (2013) comment on the important role of paleoecological data in allowing a better appreciation of historical fire regimes. These are relevant in the context of climate risk assessments, adaptation planning, biodiversity conservation or indigenous culture and heritage.

2.1.2. Forest dynamics

Many studies utilise a range of proxies such as pollen and charcoal from sediment cores that detail centennial to multi-millennial changes in forest community composition and human impacts on landscapes (e.g. Bush et al., 2016; Ma et al., 2016; Hennebelle et al., 2018; Lézine et al., 2019; Castilla-Beltrán et al., 2020). In some cases, such records can be combined with historical and archaeological records and socio-economic data (e.g. Poska et al., 2018) to provide the broader context required for forest restoration. This approach may reduce uncertainty by furnishing a long-term perspective (Davies, 2011) on surviving forest remnants, apparently extended ranges of some species, or changes in the cultural landscape (Brown, 2010; Castilla-Beltrán et al., 2020). One specific example is the use of paleo-evidence combined with modelling to conclude that *Abies alba* may provide important ecosystem services into the future where other more drought sensitive species may not (Ruosch et al., 2016). Another example involved Examination of paleoecological information (pollen and fungal spores) from the Ashtead archaeological site in Surrey in England, Waller (2010),suggesting that a "true" baseline over the Common Era was lacking due to the continuous changes in the cultural landscape over this period and that examination of paleo-records can provide longer-term context against which to compare current conditions. A growing emphasis on better managing forests to improve carbon sequestration and storage can also be informed through dendroecological analysis of how trees are responding to climate and climate extremes (Case et al., 2021; Young and Ager, 2024).

As a discipline, dendroecology has significantly contributed to knowledge of forest dynamics in a variety of ways and for a wide range of environments (Amoroso et al., 2017). These include knowledge of species age ranges, forest decline and tree mortality (Srur et al., 2020; Camarero et al., 2017), patterns and drivers of establishment, the importance of canopy gaps for recruitment, regeneration, structure and species composition (D'Amato et al., 2008; Baker and Bunyavejchewin, 2017; Martin-Benito et al., 2022), and the long-term legacy of forest disturbances (Martin-Benito et al., 2022; Schurman et al., 2018) and disturbance regimes (D'Amato et al., 2008; Srur et al., 2020; Nguyen et al., 2023). Another contribution has been improving our knowledge of interactions between past management practices and natural processes (Conedera et al., 2017). These studies have clear relevance for policies aiming to restore forests to a pre-industrial era state. Dendroecological studies have also made major contributions towards understanding the periodic nature of some insect outbreaks, their impact on woody growth, as well as quantification of their impact and identification of climatic triggers of outbreaks (Speer and Kulakowski, 2017).

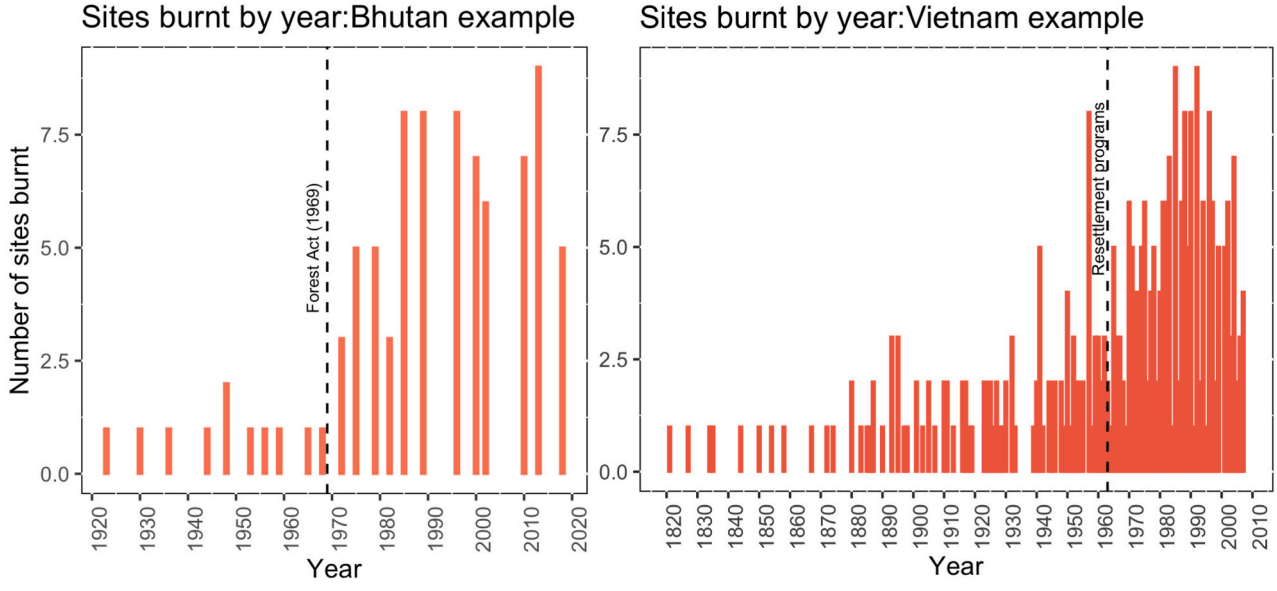

Fig. 2. Demonstration of how tree-ring fir scar records can be used to detect impact of policy change. Left: The introduction of the Forest Act 1969 in Bhutan restricted human activites in and near forests, leading to an increase in fuel load and the number of broadscale fires. Right: A sustained increase in fires in the Bidoup Niubar National Park region in Vietnam coincided with policies that resettled people from urban areas into regional areas. This increased ignition sources in the regional areas. See Tenzin et al. (2024) and Nguyen et al. (2023) more detail.

2.1.3. Climate sensitivity

Dendroecology has also been used to assess the climate sensitivity of different species and forest types, something that is becoming increasingly urgent as climate changes. Extreme climate events can alter the trajectory of forest development (Pederson et al., 2014) and result in widespread mortality events, such as those experienced by *Austocedrus chilensis* in response to successive seasons of drought and hot conditions in Patagonia (Srur et al., 2020). These studies can help identify what species, or parts of a species' range, are most likely to be sensitive to climate change (Pederson et al., 2020), or when specific management interventions, such as tree thinning, are likely to reduce vulnerability of individual trees to drought and/or heat (Martín-Benito et al., 2010; Andrews et al., 2020).

Numerous studies have also examined the chracteristics of different species within a mixed forest or forest characteristics that make individuals more sensitive to water stress and drought (Sánchez-Salguero et al., 2012; Rodríguez-Catón et al., 2015). In the urban context, many authorities have been able to utilise dendroecological methods to evaluate how well species currently used as street trees are likely to respond to climate change going forward (Nitschke et al., 2017; Monteiro et al., 2017), and dendrochronology has been used to track urban evolution through heat island impacts on tree-growth (Schneider et al., 2022).

2.2. Application of high-resolution paleohydrology to water resource management

Policy and practices for the storage, allocation and distribution of water depend on the collection and analysis of hydrometric data. The use of these data to estimate water supplies and the probability of extreme conditions relies on the foundational concept of stationarity, that the statistical characteristics of hydrological processes and observations are consistent over time. Engineering hydrologists have methods for "naturalizing" streamflow data to account for regulation, dams and diversions that affect the stationarity of hydrometric time series. Climate change is a different problem, however, since its effects are transient, not watershed-specific nor easily quantifiable (Milly et al., 2015; Slater et al., 2021). The weakness of the stationarity assumption became increasing apparent as instrumental records increased in length (Klemeš, 2014). A disconnect between reality and stationarity is well known to paleo-scientists; proxy hydroclimatic data demonstrate that instrumental weather and water records represent a small sample of low-frequency variability and extreme values. Various natural archives preserve signals of hydroclimatic variability and extremes. The sources of annually-resolved records are tree rings, ice cores, banded corals, laminated speleothems and varved sediments (Bradley, 2011; Pabón-Caicedo et al., 2020).

Research in paleohydrology has improved our knowledge of regional hydroclimatic regimes, projections of future climate, and interpretations of the observed reference hydrology and climate (Loaiciga et al., 1993). The value added by a longer perspective, and the fundamental necessity of water for life, gives all research in paleohydrology societal relevance (Bradley et al., 2003; Oldfield and Alverson, 2003), informing decision making about water allocation, apportionment, conservation, conveyance and storage, source water protection and preparedness for flooding and drought. Advances in the extent and density of large area networks of paleo-sites, new proxies, and novel approaches to paleo-data disaggregation and model calibration have improved the potential for practical applications.

Water supply, the allocation of water amongst users in a watershed and apportionment amongst states, provinces and nations, requires data on the distribution and flow of surface water. Irrigation from surface water and hydropower generation also rely on reliable annual river flow forecasts, which when based on historical time series, do not account for the persistence of dry/wet conditions evident in pre-instrumental records (Nasri et al., 2020). Paleohydrology has exposed circumstances where river basin yield has been overestimated from short gauge records. The best-documented instance is the 1922 Colorado River Compact. Similarly, a tree-ring reconstruction of autumn/winter rainfall over inland southwest Australia suggests that the twentieth century was the wettest of the last seven and risk of extended droughts in the region is probably much higher than currently understood (O'Donnell et al., 2021).

Proxy streamflow data are well suited to addressing a major challenge for water allocation in large river basins: concurrent hydrological drought in tributary sub-basins (McCabe et al., 2020). From a comparative analysis of independent tree-ring reconstructions of warm/cold season flows of the North and South Saskatchewan Rivers (western Canada; Kerr et al., 2021) determined that over the past seven centuries, high flows were synchronous more often than low flows, although the worst-case scenario of drought spanning both basins has occurred periodically. Similar tree-ring studies of adjoining river basins in Arizona (Meko and Hirschboeck, 2008) and California (Woodhouse et al., 2020) revealed consecutive years of basin-wide drought, a scenario that today could not be offset by accessing water supplies from an adjacent source region.

Large area networks of paleoclimate sites have led to a proliferation of gridded reconstructions of hydroclimate also known as drought atlases. Inspired by the prototypical North American Drought Atlas (NADA; Cook et al., 1999, 2007), similar atlases have been developed from networks of tree-ring chronologies for nearly every drought-prone region of the world, including Asia (Cook et al., 2010), eastern Australia and New Zealand (Palmer et al., 2015, 2024), the Canadian Prairies (Kerr et al., 2021), Mexico (Stahle et al., 2016), South America south of 12°S (Morales et al., 2020) and Europe (Cook et al., 2015). These drought atlases have spawned various analyses of the spatial and spectral dimensions and of pluvials and drought (King et al., 2024; Smerdon et al., 2015; Anchukaitis et al., 2024; St. George et al., 2010; Fye et al., 2003).

Much of the research in paleo-hydroclimatology has reached a common conclusion that water resources management and planning have been based on an underestimation of the severity of excessively wet and dry conditions, disregarding the impacts of global climate change (e.g. Allen et al., 2020; Hanel et al., 2018; McCabe et al., 2020; O'Donnell et al., 2021). More recent studies, however, have reached a different conclusion. These reconstructions, from updated paleoclimate networks or new sites and proxies, indicate that extreme events occurring since the onset of the 21st century are unprecedented in the paleo-record. An example, of an "unprecedented" event, that drew the attention of policy makers in two countries, was flooding in the transboundary Souris Rivers Basin in 2011. High water levels far exceeded those in gauge records and severely tested flood control structures. In response, the Governments of Canada and the United States established a task force to re-evaluate the existing international agreement for water supply and flood control. In their final report, the International Souris River Study Board (2021) referred to two tree-ring studies, concluding that the climate of the basin "fluctuates cyclically between dry and wet states" and that "within any given 100-year subset of the paleoclimate record, conditions reflect considerable hydroclimatic variability in the basin and long-term persistence in hydroclimatic trends". Subsequent tree-ring research (Sauchyn et al., 2024) has confirmed the anomalous magnitude of the excessively wet conditions of 2011 (Fig. 3). It is by far the largest positive anomaly in a tree-ring record spanning 1690 to 2021, despite the fact that tree-ring records typically underestimate flood severity.

This recent shift in the outcomes and interpretation of some paleo-records suggests that a signal of global climate change is emerging in tree-ring reconstructions of hydroclimatic variables (e.g. Touchan et al., 2011). The uniqueness of these recent events, in the context of the paleo-record, is likely a regional manifestation of the anticipated and projected hydroclimatic response to greenhouse gas warming (Zaitchik et al., 2023; Slater et al., 2021). Climate models project increased precipitation intensity and an amplification of hydrological cycles (Marvel et al.,

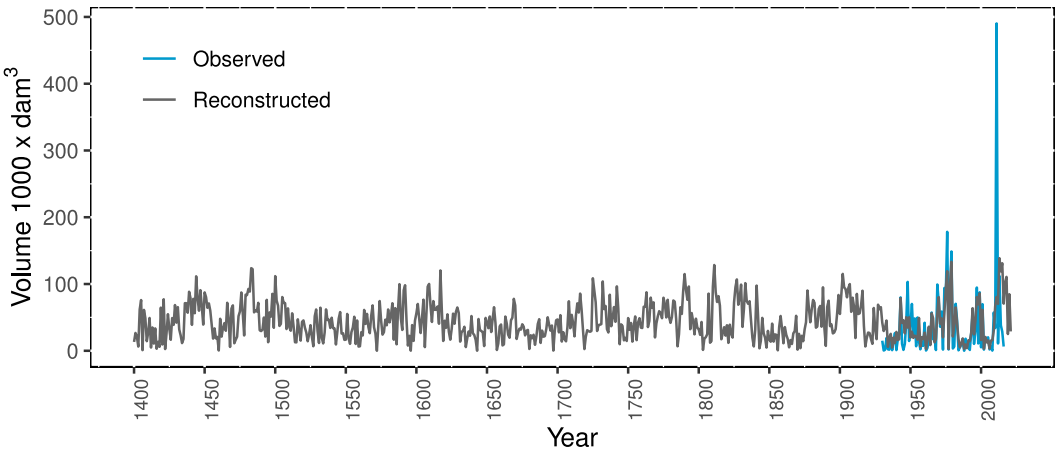

Fig. 3. Reconstructed (1400–2021) and observed (1930–2016) annual streamflow (dam^3 × 1000) of the Souris River above Boundary Dam (Saskatchewan). Sources: Sauchyn et al. (2024) and Saskatchewan Water Security Agency, respectively.

2019). Although the link to excessive runoff is modulated by local conditions, and thus is complex, anthropogenic climate change has been implicated in recent flooding events (Gillett et al., 2022).

2.3. *Paleo-information from wetlands for decision making*

Wetlands include all natural and man-made terrestrial and coastal waters (Ramsar Convention on Wetlands, 2023), are some of the most biodiverse ecosystems on Earth (Balian et al., 2007), and are integral to human livelihoods. They provide diverse ecosystem services ranging from water provisioning and regulation, transportation, food security, hazard protection, climate resilience, health and well-being, and economic benefits (Ramsar Convention on Wetlands, 2018; Wetlands, 2021).

From a paleo-perspective, each type of wetland typically accumulates allochthonous (e.g. sediments, pollen, pollutants) or autochthonous (e.g. chemical precipitates and biological remains) materials as sedimentary deposits over time. The sediment accumulated can be continuous (e.g. Fritz et al., 2012) or discontinuous (e.g. Srivastava et al., 2017), and records a history of the wetland and surrounding environments. Many wetland types can also record periods of non-accumulation, such as wetlands drying out (e.g. De Deckker et al., 2011) or where zones in which accumulated sediment moves laterally (e.g. Valenza et al., 2020). Wetlands can also suffer from active sediment removal caused by natural erosional events (e.g. Sawai et al., 2023) and deflation (e.g. Cohen et al., 2022) or through human activities such as dredging (e.g. Turner, 2022). It is the accumulation of this material that allows a longer-term perspective on environmental change to be determined.

Wetland diversity is under extreme threat from a suite of individual or multiple interacting stressors (Reid et al., 2019). Paleo-data is central to improving wetland management and policy. Papers from various Special Issues on paleolimnology (e.g. Special issues edited by Battarbee and Bennion, 2011; Holmes et al., 2013; Gell and Finlayson, 2016; Larocque-Tobler, 2017; Davidson et al., 2018; Paterson et al., 2020; Chen et al., 2022; Aránguiz-Acuña et al., 2024) highlight the difference between the pre-anthropogenic wetland condition and changes imposed by anthropogenic activities and changes in climate (Cohen et al., 2022; Luo et al., 2022). This helps to identify appropriate management or intervention triggers (Davidson and Jeppesen, 2013; Bennion et al., 2017). An important realization is that wetland management typically occurs after a wetland has been negatively impacted by human activities that were initiated and escalated prior to the collection of monitoring information (e.g. Bennion et al., 2011; Whitmore et al., 2020; Bourman et al., 2022). Knowledge and data of when and how humans began to impact wetlands (e.g. Dubois et al., 2017) is of paramount importance and can largely only be derived from paleo-data directly from the affected wetlands.

Paleo-records preserved within wetlands can provide vital clues to better understand the nature of local or regional changes. For example, readily fossilised and preserved taxa such as vertebrates and invertebrates, plant macrofossils and pollen (Smol et al., 2001, 2002) and biochemical signatures (e.g. pigments) retrieved from lake sediment cores have provided some scope for exploring changes in biodiversity. More recently, environmental or sedimentary deoxyribonucleic acid (eDNA or sedDNA) techniques have offered opportunities to determine whole of ecosystem change analysis or analysis of changes in specific taxa through time (e.g. Capo et al., 2023). This information can be used to evaluate variability and ecosystem dynamics internal and external to the wetland, timing and rates of local extinctions or colonization, population fluctuations of key species, and introductions and expansion of invasive or exotic species (e.g. Ficetola et al., 2018; Orlando et al., 2021; Giguet-Covex et al., 2023). If calibrated appropriately, this information can replace long term and costly field monitoring and establish baseline ecosystem information under different climate or environmental conditions that can inform adaptive and dynamic wetland management (Capo et al., 2021).

Paleo-records from wetlands can also be used to track climate variability, environmental degradation, and human use that can directly or indirectly affect groundwater and freshwater resources and ecosystems that feed wetlands (Baggio et al., 2021; Fluet-Chouinard et al., 2023; Jasechko et al., 2024). For example, paleo-records that capture variations in salinity (Wilkins et al., 2013), eutrophication (Davidson and Jeppesen, 2013), acidification (Birks et al., 1990), sedimentation (Ficetola et al., 2018) and metal pollution (Yang et al., 2022) can provide information about declining availability and/or quality of freshwater for human use and the environment. Wetland paleo-records can also provide detailed information on the local and regional hydrology, and be used to determine water balances, source contributions and variability in surface and groundwater systems (e.g. Gouramanis et al., 2010).

Many nations are now investing heavily in various means of natural carbon sequestration, by for example, establishing and protecting coastal blue carbon ecosystems (e.g. mangroves, saltmarshes and sea grasses; Macreadie et al., 2021) and teal carbon ecosystems (e.g. inland wetlands; Nahlik and Fennessy, 2016). In this context understanding past carbon variability is therefore crucial. Analysis of wetland paleo-records can demonstrate that the magnitude of carbon storage has varied with climate and human impacts, thus contributing important data for establishing baseline national and international carbon account reporting.

Many nations are also conducting climate risk assessments (e.g. New

Zealand Ministry for the Environment, 2020a; UK Government, 2022) and using this information to develop national adaptation plans and to manage the impacts of anthropogenic climate change (e.g. UNFCCC, 2023). Most climate risk assessments focus on impacts on the natural environment, including wetlands (e.g. New Zealand Ministry for the Environment, 2020b). The risk assessments typically rely on short-term historical observation data and climate model projections (e.g. New Zealand Ministry for the Environment, 2020a). Complementing these data sources with paleo-hazard information (e.g. floods, (Wilhelm et al., 2022); droughts, (Wilkins et al., 2013); avalanches, (Fouinat et al., 2018); storms, (Liu and Fearn, 1993); and fire regimes (Conedera et al., 2009)) from wetlands can provide a longer-term perspective on the impacts, duration and natural recovery rates of these systems that may not be covered by the short-term observation records (Sabatier et al., 2022).

Wetlands can also preserve past records of geophysical hazards with long recurrence intervals, such as earthquakes (Moernaut, 2020), volcanic eruptions (Leicher et al., 2021) and tsunamis (Kelsey et al., 2005; Bondevik et al., 1997). Interpreting these long records of geophysical hazards can inform risk estimation of hazards not witnessed or recorded in the historical or observational records. Wetland paleo-records can also preserve evidence of cascading and compound hazards (Sabatier et al., 2022) that can assist with evaluating the future risks and impacts of these events and natural recovery rates of the natural systems. Such information can forewarn local communities and administrative authorities about the risk of these potential hazards. This contributes to "Understanding Disaster Risk", Priority 1 of the Sendai Framework for Disaster Risk Reduction, and to local and national risk assessments for appropriate adaptation planning (e.g. UNDRR, 2015).

3. Embedding paleoscience information into decision making

Much has been written about the science-policy divide and barriers to engagement (e.g. Stringer et al., 2006; Long, 2009; Davies, 2011; Hoffman et al., 2021; Gillson and Marchant, 2014; Williamson and Nelson, 2017; Copes-Gerbitz et al., 2022; Kiessling et al., 2023; Månsson et al., 2023). There are, however, relatively few published examples of paleo-data actually being incorporated into policy and decision making (Lindbladh et al., 2013; Meko et al., 2022; Woodhouse and Pederson, 2018). However, the studies described in the above section clearly demonstrate some of the valuable insights that paleo-data offers. Several of the studies also point to impediments to embedding paleo-data into good functional decision-making. These constraints can be used as starting point from which to devise a way forward.

In this section, we draw on the insights from many of the above-cited studies to devise a general and adaptable way to better embed paleo-science information into policy and decision making around addressing the Earth's grand environmental and climate challenges. Underpinning our proposition is the recognition that both paleo-scientists and decision makers want the best outcomes. We recognize that there is a wide diversity of government styles and arrangements that have unique hierarchical and legislative frameworks, and that these span diverse social, economic, political, cultural (including religious), ideological and historical elements. We also acknowledge that as authors, our experience is

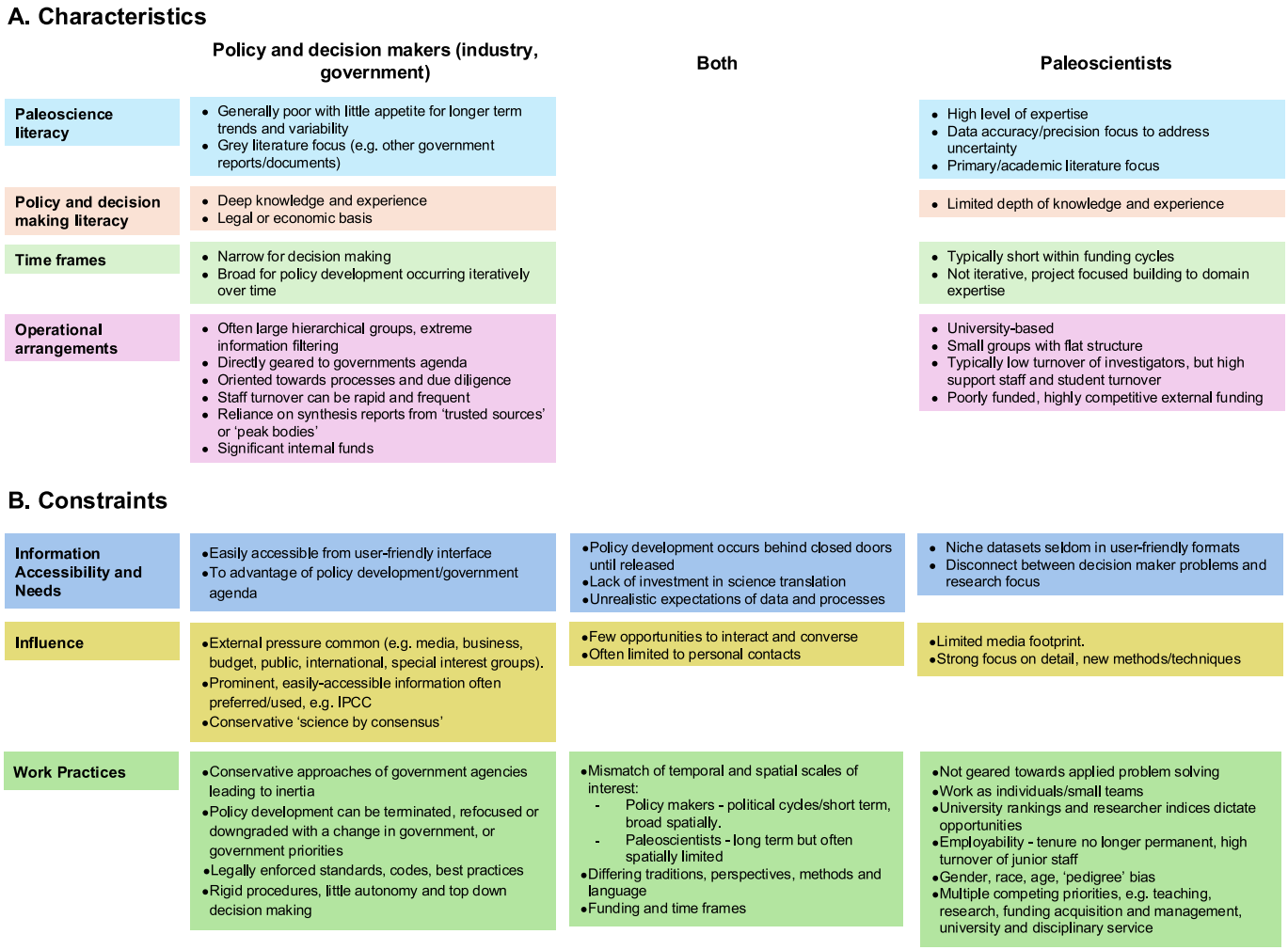

Fig. 4. General characteristics and constraints of the environments of paleo-scientists and policy decision makers. A. Characteristics. B. Constraints.

limited to economically and politically-stable Western governmental systems. What we propose is deliberately broad and does not focus on niche areas, decision-making systems or specific problems.

We argue that a first step to identifying specific barriers to the uptake of paleo-science information in policy decision making is to appreciate the general environments and characteristics in which policy and decision makers and professional paleo-scientists work (cf. Kiessling et al., 2023). Fig. 4A aims to capture the very different operating environments and expertise of policy makers and paleo-scientists, demonstrating the complexities of working together faced by the two apparently disparate groups. We have grouped these characteristics under four themes related to literacy, time frames and operational arrangements, and various references to these are found in the literature cited above. A few of the key differences in the two groups include: their preferences, or need, for data in particular formats (Gillson and Marchant, 2014; Kiessling et al., 2023); circles of interaction/contacts, operational legacies, procedures and legal requirements (Hoffman et al., 2021); different areas of specialised expertise and relative ignorance outside of this expertise (Long, 2009; Davies, 2011; Gillson and Marchant, 2014; Kiessling et al., 2023); hierarchical arrangements; time-frames, spatial scales of interest; funding and resource issues and uncertainty (Long, 2009).

Based on these characteristics, three general categories of constraints for incorporating paleo-data in policy decision making can be distinguished (Fig. 4). These are:

- Information and its accessibility
- External and internal organizational factors
- Work practices

These constraints strongly reflect the different characteristics and priorities of the two parties, and some of them are more relevant to one party. Policy development behind closed doors, for example, can limit the input sought by policy makers from scientists, but can also affect the relative awareness of scientists of the value of their data/information to the policy development process (Fig. 4). Similarly, a lack of investment in translating the science by both paleo-scientists and decision makers (c.f. Gillson and Marchant, 2014; Stringer et al., 2006) can contribute to a lack of interaction between the two groups. In this respect, the importance of a clear, succinct and direct message based on the paleo-science for the decision maker cannot be under-rated. Clear messages engage a decision maker's interest and foster further discussion and engagement. The need for and access to data differs between the two groups, creating difficulties for its uptake. The same is often true in relation to the different temporal and spatial scales of information required or used by the two groups. There is also often a considerable disconnect between academic and policy/decision-making traditions, perceptions and language (c.f. Briley et al., 2015). Greater emphasis on academic debates by paleo-scientists can be disorientating and considered irrelevant by decision makers. A lack of visibility of paleo-scientists, whether due to their lack of engagement with policy and decision makers, not being visible on social media or to issues associated with work practices that decrease opportunities for visibility, also mean that paleo-science is more easily overlooked as a source of policy-relevant information and data. Many of these constraints have previously been identified in relation to the science-policy gap more generally (Rose et al., 2018).

These constraints and characteristics (Fig. 4) provide the basis for navigating a way forward. This begins with identifying the available opportunities for action and the likely result of taking action (Fig. 5). These identified opportunities are generally consistent with recommendations from the broader literature around better using evidence from the natural or social sciences to inform policy (e.g. Briley et al., 2015; Vogel et al., 2016; Rose et al., 2018; Oliver and Cairney, 2019). Overwhelmingly, opportunities are all based around greater interaction. Interaction and communication can help break down seemingly entrenched traditions. For example, science translation can occur through placements of paleo-science students and academics in industry or government, or through their attendance at industry workshops and conferences, not just scientific meetings. Other efforts have come from scientists themselves, for example, a pamphlet targeting forest managers https://masswoods.org/sites/default/files/pdf-doc-ppt/Restoring-Old-Growth-Characteristics.pdf. Decision makers could also attend paleo-focused conferences. There may also be a range of government-funded opportunities for exchanges, such as fellowships in industry or industry-focused grant funding. Likewise, secondment of policy specialists to scientific teams could improve paleo-scientists' understanding of the policy context. It is also likely to increase scientific awareness of the importance of providing and maintaining user-friendly data and information interfaces as well as high-level and easy to understand and accurate tools and infographics, which in turn are likely to increase the uptake of paleo-data in decision making (Rose et al., 2018; Oliver and Cairney, 2019).

Co-design and co-production are also important processes whereby stakeholders come together to grow a shared vision through which to design and produce a process or product (Steen et al., 2011). This can help change any inappropriate a priori assumptions, validate information use and understanding, and ensure materials and methods are understood by all parties, resulting in better appreciation of other viewpoints/standpoints, and a better fit between policy and available scientific evidence. The process involves significant learning by all parties, and has the potential to help overcome several of the barriers to better incorporating paleo-science into decision making for policy, including translation issues, information exchange, broadening teams and ensuring user-friendly data becomes more available. It can also lead to long-term professional relationships and broaden the interaction amongst policy makers and paleo-scientists. However, co-design and co-production can only proceed once links have been established between

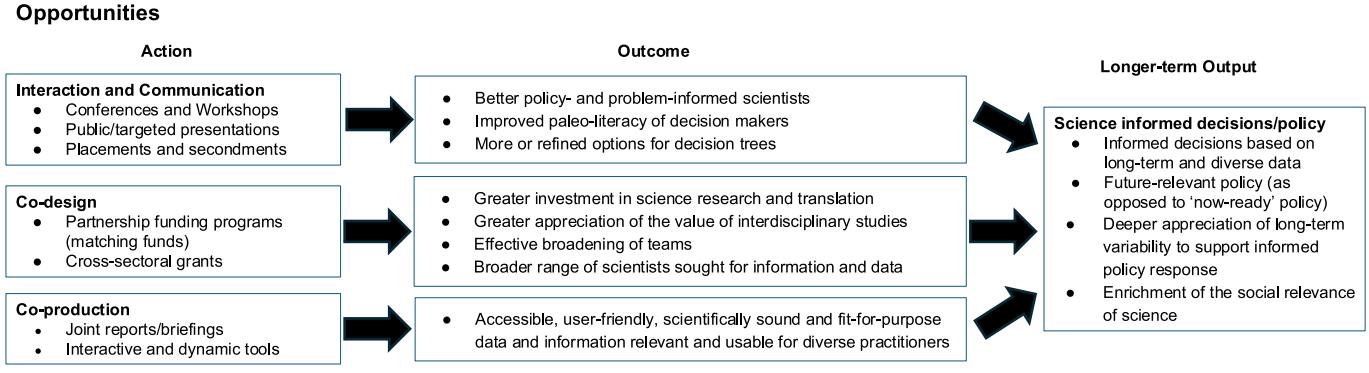

Fig. 5. Opportunities available to help improve the uptake of paleo-data.

parties. It is also important to note that the complexity and protracted nature of learning about and engaging in the codesign learning process is often not fully appreciated (Roux et al., 2022). Ultimately, though, these processes should result in more informed decision making, better policy and increased awareness of the social relevance of paleo-science. Guides for undertaking the co-design and co-production process are available, as are various case studies (e.g. Karrasch et al., 2017; Boulter et al., 2023).

Although we have identified important opportunities for improving the uptake of paleo-science through a better understanding of its relevance, these opportunities cannot immediately remove several of the barriers, particularly some of those associated with work practices and operational arrangements. It is therefore equally important to acknowledge that dealing with some of the barriers may require a longer time frame and be iterative, while others may remain intractable. Some of the more obvious longer-term and more difficult to resolve issues relate to the nature of working as a paleo-scientist within the university system with its multiple competing demands, the hierarchical nature of industry and government organizations and high staff turnover (Fig. 4).

An important part of the process is identifying and documenting remaining constraints, and being realistic about elements around work practices (in particular) that are difficult, or perhaps even impossible, to change. Ultimately, there should also be an evaluation of how well the process worked in specific cases and what can be improved upon. Iteratively working through the complexities of the science-policy divide will greatly diversify the information available for decision making, provide alternative management and decision options and thereby drive science-informed policy for better long-term and sustainable outcomes.

4. Conclusions

Through reviewing a variety of studies, we have demonstrated the wide applicability of paleo-data in three general field of research and the power of longer-term (beyond recent monitoring and modelling) data sets as a valuable tool for basing policy and for making decisions. Paleo-data also has much to offer in other areas such as pollution tracing, climate and geo-hazard risk assessments and atmospheric carbon monitoring. The relatively poor record of consideration and inclusion of the insights this data offer in policy and decision making is due to a range of barriers that has previously been identified for other areas of science. Key amongst solutions to addressing barriers is greater communication and interaction amongst paleo-scientists and decision makers in government and industry. This requires time and resourcing, but will lead to the consideration of a much broader range of data and information sources, as well as greater scientific literacy amongst decision makers and awareness of policy and decision-making processes by scientists. This in turn would result in better quality decisions and policy responses to a range of significant issues that impact societies and the environment. We have provided a general process through which improvements can be made. We recognize that we have done so through lens of paleo-scientists from economically stable Western countries, and that under other conditions embedding paleo-science into policy and decision making can be more challenging, but equally rewarding if successful.

CRediT authorship contribution statement

K.J. Allen: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Conceptualization. **C. Gouramanis:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Conceptualization. **D. Sauchyn:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

All authors of this article are serving as guest editors for the Special issue to which this article has been submitted. In addition, Allen is on the editorial board of the journal.

Data availability

No data was used for the research described in the article.

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