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Exploring the Interface Between Planetary Boundaries and Palaeoecology

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ABSTRACT

The concepts of planetary boundaries are influential in the sustainability literature and assist in delineating the 'safe operating spaces' beyond which critical Earth system processes could collapse. Moving away from our current trajectory towards 'hothouse Earth' will require knowledge of how Earth systems have varied throughout the Holocene, and whether and how far we have deviated from past ranges of variability. Such information can inform decisions about where change could be resisted, accepted or where adaptation is inevitable. The need for information on long-term (Holocene) change provides an interface for palaeoecology and sustainability that remains underexploited. In this position paper, we explore this interface, first discussing the need for long-term perspectives and introducing examples where palaeoecology has been used in defining safe operating spaces and constraining limits of acceptable change. We describe advances in quantitative methods for analysis of time-series data that strengthen the contribution of palaeoecology to the concepts of planetary boundaries and safe operating spaces. We consider the importance of issues of scaling from landscape to regional and global scales in operationalising planetary boundaries concepts. We distil principles for this field of research going forward and introduce three case studies which will form the basis of research on these topics.

1 | Introduction

As the world continues on its unsustainable trajectory towards 'hothouse Earth' (after Steffen et al. 2018), it is essential to determine the limits of resilience for key biological and environmental processes and to plan adaptation pathways when critical thresholds are crossed. The planetary boundaries (PB) framework was developed with the aim of defining the limits of critical Earth system processes, providing humanity with a designated 'safe operating space' (Rockström et al. 2009a, 2009b, 2023; Steffen, Richardson, et al. 2015; Steffen, Broadgate, et al. 2015). This delineation aids in establishing pathways that could effectively stabilise Earth system processes and guide adaptation where boundaries are crossed. Deviation beyond these limits may lead to destabilisation or even collapse of key processes, or novel states may emerge. The nine PB (see Figure 1) encompass the interrelation and complexity of the Earth systems and its biophysical components. Since its initial assessment in 2009, an increasing number of these PB have been crossed; a 2023 assessment underscores that only three boundaries remain within a safe operating space (see Figure 1) (Richardson et al. 2023). Noteworthy advances since the concept's inception include the integration of a social justice element aiming to develop safe and just operating spaces (Raworth 2012).

Steffen et al. (2018) argued that the stabilisation of the systems necessitates return to 'Holocene-like' conditions (Steffen et al. 2018), while others argue that this is impossible and that the emergence of new conditions is inevitable (e.g., see Ellis 2024). In either case, challenges arise in defining how far we have departed from Holocene conditions in the absence of long-term data spanning key environmental and social transitions since the start of the Holocene. These transitions include (but are not limited to) the Great Acceleration circa 1950 (Steffen, Richardson, et al. 2015), industrialisation and European colonisation (C17th–C19th), the Medieval Climate Anomaly (C10th–13th), the expansion of metal working (6—1 ka), the mid-Holocene altithermal (9—5 ka), the beginning of agriculture (10+ ka) and the extinction of megafauna (beginning in the Pleistocene), all of which represent significant, cumulative human and environmental impacts on Earth system processes, raising questions about the validity of preanthropogenic baselines as conservation and sustainability targets. Such discussions contributed to the rejection of the Anthropocene as a geological epoch, although the Anthropocene concept persists as a useful boundary object for flagging the ubiquity of human impact (Gibbard et al. 2022) and deep histories of human and nonhuman entanglement (Braje and Lauer 2020).

Without longer-term data and agreement on what constitutes Holocene ranges of variability, it is difficult to define what constitutes novel conditions, and this in turn creates difficulties in defining safe operating spaces. Comprehensive knowledge of processes spanning the Holocene proves invaluable in exploring the variability and resilience of key parameters. Palaeoecology, the study of past ecology and environment, provides insights into long-term change in key landscape parameters including vegetation abundance and composition (land cover), fire regimes, biogeochemical cycles, water quality, pollution and soil erosion (Dearing 2006; Dearing et al. 2006). Palaeoecology utilises 'proxies', that is, measurable variables that are biological, geochemical and molecular in nature, contained within various environmental archives (Meadows 2014). Common examples used in palaeoecological

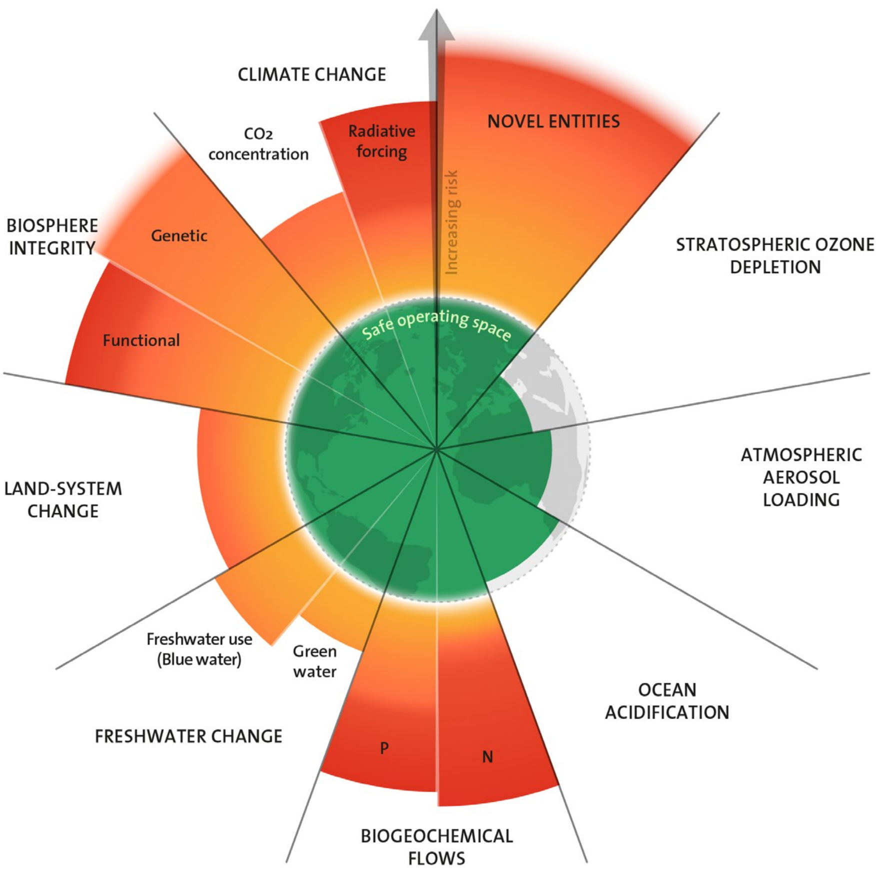

FIGURE 1 | The 2023 update to the planetary boundaries. Azote for Stockholm Resilience Centre, based on analysis in Richardson et al. (2023). Licensed under CC BY-NC-ND 3.0.

studies include fossil pollen, charcoal, stable isotopes, diatoms and spores preserved in lake sediment records to reconstruct long-term changes in vegetation, fire history, climate and herbivory (Birks 2012).

Such approaches are complemented by other time-series data covering the recent past including, but not limited to, long-term monitoring and satellite imagery, as well as insights from historical documentary sources, repeat photographs and archaeology. For example, with its access to the material traces of human–environment interactions and multispecies entanglements over the entirety of our own species' history on Earth and beyond, archaeological records offer equally critical opportunities to explore at both site and landscape scales of analysis of how human activity has influenced changes in biodiversity (Lyman 2006, 2012; Millhauser and Earle 2022) and many other dimensions of environmental change (Braje 2024). Studies on the latter include examples of significant anthropogenically driven regional changes to the nitrogen cycle due to deforestation, agricultural intensification and other land use management practices long before the Industrial Era with long-term consequences for both freshwater (Guiry et al. 2020) and terrestrial environments (Guiry et al. 2018). Additionally, archaeologically informed long-term studies of human–environment interactions have a key role to play in identifying land and resource use strategies that have proved to be ecologically sustainable over hundreds of years (Brewington et al. 2015; Jacobson 2022), examples of where and when human activities have enhanced regional biodiversity over the long term (Roberts et al. 2017) and how human communities have 'weathered' severe climate change in the past although much remains to be done in refining these approaches (Petek-Sargeant and Lane 2021; Rivera-Collazo 2022).

These methodologies enable researchers to explore the drivers and human dimensions of land cover change and facilitate the study of environmental change over decadal to millennial timescales (Gillson and Marchant 2014). The combination of these methodologies potentially allows for a much needed temporal continuum spanning from millennia to months, thereby improving our understanding of landscape change and variability at localised and regional spatial scales. Furthermore, the integration of cross-disciplinary approaches enhances our understanding of past and present management practices, both beneficial and adverse.

This nuanced understanding proves crucial for informing decision-making processes that consider whether and/or how far we have exceeded Holocene 'safe operating spaces' and are in the realms of adapting to no-analogue conditions. Knowledge of such variability could help in mapping out trajectories that could stabilise essential Earth system processes and the associated ecosystem services (Dearing et al. 2014; Cooper and Dearing 2019). Linking palaeoecological proxies to ecosystem services (the provisioning, supporting and regulating benefits provided by nature) provides an interface for engagement between palaeoecologists and those working in the sustainable development arena. Such holistic perspectives expand our comprehension of the range of national and regional interventions feasible for landscape management today and lay foundations for informed strategies in the future, which include adaptation to novel conditions when a return to Holocene-like conditions is not possible or desirable.

Although not all PB as defined by Rockström et al. (2009a, 2009b) are amenable to these approaches, land system change, freshwater use, biotic integrity and biogeochemical flows, while challenging, could potentially find representation in palaeoecological records, for example, as could climate change, albeit indirectly. Archaeological and historical records can provide insights and different spatial and temporal scales on land system change and can offer perspectives on long-term human responses and contributions to climate change. The question of what constitutes a 'novel entity' could likewise benefit from a long-term perspective (van Leeuwen et al. 2005; van Leeuwen et al. 2008).

In this position paper, we argue that exploring Holocene ranges of variability can assist in delineating safe operating spaces and that future management strategies can be substantially improved through insight from historical ranges of variability. Furthermore, long-term data can help in envisioning plausible scenarios of climate and land cover change, including situations where novel combinations of climate change and land use create no-analogue conditions that require adaptation. Our aim is to examine the synergy between the concept of safe operating spaces and palaeoecology, aiming to contribute to the operationalisation of the PB concept. We explore utilisation of long-term data from the early Holocene onwards to establish ranges of variability and trajectories of change across a range of various temporal and spatial scales. Employing the analyses of temporal variation, we can identify regime shifts and relate our findings to tipping points in key variables, such as biodiversity loss, land cover change, biogeochemical flows and freshwater use. Concurrently, our investigation extends to interrelated aspects such as water management, restoration and the interlinkages between restoration and sustainable utilisation of ecosystem services, opening potential for alignment with the broader framework of the sustainable development goals.

While acknowledging the imperfect nature of the past as an analogue for the future, long-term data prove essential in assessing the extent of current deviation from past conditions, thereby aiding the decision-making process—whether to attempt a return to former states of variability or adapt to emerging novel conditions. It remains irrefutable that ecological and climatic processes possess finite resilience; at some point or combination of stressors, system collapse and reorganisation are inevitable. Hence, a pivotal determinant for effective planning and adaptation lies in identifying the thresholds and behaviours indicative of such occurrences if we are to effectively face the challenges and opportunities of the Anthropocene. Presently, humanity faces unprecedented challenges manifested in climate variation, extreme events, population size and the magnitude of our impact on Earth system processes. Yet, we also have access to clean energy, new methods of food production and technological advancements that provide opportunities for adaptation that can draw on a wealth of experience from generations past as well as the ingenuity of current and future. Mapping the way forward will require an understanding of where we have come from as well as an open-minded approach to where we are heading in the future.

Here, we first examine the application of thresholds/limits concepts through the lens of biodiversity conservation, ecological restoration and ecosystem management. We then introduce quantitative approaches to detecting thresholds in time-series data of palaeoenvironmental variables. We also discuss issues of scaling between global and regional levels in the context of operationalising PB concepts. Finally, we introduce three case studies that serve as illustrative examples, selected in large part because of the range and quality of the records available. These cases demonstrate the integration of palaeoecology with other forms of knowledge, showcasing how the interdisciplinary approach enhances our understanding of the trajectories and drivers of change over time. We use these discussions to draw out five principles that could guide research.

2 | Defining 'Safe Operating Spaces' Based on Palaeoecological Data

The use of long-term data in managing ecosystems within limits is well established. Examples include historical range of variability (HRV), limits of acceptable change, thresholds of potential concern (TPC), indicators of resilience loss and safe operating spaces. These concepts are overlapping and interrelated in that they all attempt to delineate an acceptable range of variability, in contrast to earlier approaches that defined fixed targets such as a particular ecological community or population size.

2.1 | Historical Range of Variability

The first step towards defining a safe operating space is to establish whether a system is operating outside of its past or HRV (Keane et al. 2009; Morgan et al. 1994). Conserving a range of variability maintains broad habitat conditions so that many species may be conserved, simultaneously recognising the dynamism of ecosystems and the importance of disturbance in shaping ecosystems (Thompson, Duncan, and Johnson 2008). Ranges could cover multiple relevant time scales (Morgan et al. 1994) which palaeoecological and archaeological datasets can offer, ranging from decades to millennia, with the past c. 11,000 years (Holocene) as most relevant to the PB literature. This approach has been previously applied in various contexts, for example, fire management (North and Keeton 2008), forest management (Veblen 2003; Thompson, Duncan, and Johnson 2008) and restoration of ecosystems (Higgs et al. 2014; Millar 2014; Oliver, Dorrough, and Travers 2023). In these applications, the most relevant spatial scales are the local to landscape scales over which most management interventions operate and which are best reflected in palaeoecological records from lakes and wetlands and captured in coeval archaeological, geoarchaeological and bioarchaeological signatures. Knowing a system's HRV could provide a basis to establish the future range of variability (FRV) of the system taking into account factors that are expected to be different in the future such as climate, human population, social acceptability and exotic species (Thompson, Duncan, and Johnson 2008), thus potentially contributing to scenario planning.

2.2 | Thresholds of Potential Concern

In the Kruger National Park, South Africa, ecosystem management is governed by acceptable limits of variability in key ecological parameters. These limits, known as TPC, define ranges of acceptable ranges of variability based on current ecological knowledge, management objectives and stakeholder perspectives (Biggs et al. 2011). In the case of woody plant cover, for example, the TPC states that woody cover should not fall below 80% of its highest-ever value at any location or 30% parkwide. Using variability to guide management goals brings in a temporal dimension and paves the way for synergies with palaeoecological data. Calibrated fossil pollen data can be used to track changing tree abundance over time, information which can be used to inform TPCs (Gillson and Duffin 2007). This is especially valuable in landscapes where there are no written or historical records dating from before European colonisation, which brought massive disruptions to ecological processes and customary management, including hunting of megafauna, eradication of predators, introduction of diseases like rinderpest and policies of fire suppression, forced human settlement removals and the introduction of hard, fenced boundaries constraining movements of people and animals. Long-term data from palaeoecology can be used to identify transitions between savanna vegetation types, including water-scarce grasslands, grazing lawns, fire-maintained savannas and riparian forests (Gillson and Ekblom 2020). Archaeological and historical records can supplement these insights to help establish the nature, distribution and intensity of land use (for Kruger National Park, see, e.g., Verhoef 1986) and their changes over time (for regional approaches and global methodologies, see, e.g., Hannaford 2018, 2023; Marchant et al. 2018; Morrison et al. 2021), while also being mindful of the political ecology of conservation landscapes such as these (Meskell 2009; Lunstrum 2015). Furthermore, a multiproxy approach can help to identify the drivers of such transitions, including fire (reconstructed from charcoal abundance), herbivory pressure (reconstructed from dung fungal spores), water availability, climate and nutrient status (from isotopes and diatoms) (Gillson and Ekblom 2009a, 2009b; Ekblom and Gillson 2010a, 2010b). This information can help managers to identify potential tipping points or thresholds in ecosystem behaviour. They can then collaborate with stakeholders to decide whether such transitions are desirable or should be prevented, for example, by manipulation of fire regimes and herbivory.

2.3 | Limits of Acceptable Change

In the Murray–Darling Basin, Australia, changes in key ecological parameters extending beyond the arrival and settlement of Europeans are used in defining limits of acceptable change (Newall et al. 2015). These limits define that range of variability that is deemed tolerable by managers and are based on timescales that encompass the variability engendered in slow processes that play out over timescales of centuries to millennia (Finlayson et al. 2017). Palaeoecology and other long-term data have revealed that although wetlands are perceived as needing to permanently have fresh water, in the past, many experienced intermittent drying which is important for maintaining biodiversity (Pritchard 2021). The permanently inundated state originated in the 1920s when the wetlands became 'pegged' to the water levels in weir pools, stopping them from drying out (Gell 2020). The $10B Plan for the Murray–Darling Basin is designed to get water to wetlands, many of which have too much compared with their long-term history. The emphasis on maintaining freshwater levels diverts critical funding away from other key drivers of degradation (Gell 2020). Palaeoecological work has also revealed that some formerly freshwater wetlands have become saline due to abstraction of water for irrigation and elevated saline water tables (Macumber 1991; Gell et al. 2005), while other formerly saline systems have become artificially freshened by water from government drainage schemes (Gell 2019; Haynes et al. 2007). Parallel archaeological research has also provided important insights into the operation of the freshwater system throughout the Holocene, aiding identification of the water management approach of the recent past that is the closest analogue of precontact conditions (Bourman et al. 2022). This combined work shows the importance of using long-term data in defining limits of acceptable change and in describing the natural ecological character of wetlands that are designated Ramsar sites.

2.4 | Safe Operating Spaces

Safe operating spaces are defined at the global scale as the range of variability within which the capacity of the planet to provide life support systems is not endangered. Holocene-like conditions are used as a reference for delineating safe operating spaces because this is the only time period that is known to have supported the modern world as we know it. In order to operationalise the concept of safe operating space, it is necessary to downscale to spatial scales that can be managed or that are in the jurisdiction of political entities (see Section 6).

There are a few instances where time-series data have been incorporated into the exploration of safe operating spaces at landscape—regional scales. For example, Dearing et al. (2012) examined changes in ecosystem services over the period 1800–2006 in the Yangtze River Basin, China. They identified more than 50 ecosystem services which could be tracked using palaeoenvironmental proxies, then developed a regional regulating ecosystem service index and showed rapid degradation since 1950. Their work suggested that the regulating ecosystem service index had not been stable since the late 19th century and that critical environmental thresholds were probably crossed in the 1980s, when agricultural intensification and rapid population growth were associated with forest clearance, increased flooding and erosion, while pollution from fertilisers, mining and industry also dramatically increased (Dearing et al. 2012). Such work is relevant to the concept of safe operating spaces as it identifies the points along trajectories of change at which critical transitions occur. In a further paper, Dearing et al. (2014) defined a regional safe operating space that can be applied to time-series data. They described linear, nonlinear and threshold responses in time-series data, highlighted the importance of early warning signals in assessing environmental risk and showed evidence of these patterns in case studies from Erhai Lake catchment, Yunnan Province, and Shucheng County, Anhui Province (Dearing et al. 2014; Wang, Dearing, and Langdon 2012). Dearing et al.'s approach was also applied in the Chaohu watershed, China. They used data from long-term monitoring, surveys and anthropogenic impact records in lake sediments and identified water quality, chemical pollution and soil stability as exceeding safe operating limits at the subwatershed scale (Su et al. 2023). Their work showed heterogeneity across the watershed, with greater environmental pressure in the western areas than in the east of the watershed. As well as showing the effectiveness of Dearing's framework, the research was also important in highlighting considerations of heterogeneity and scale (see Section 6 below).

3 | A Conceptual Framework for Integrating Palaeoecological Data and PB

Social-ecological systems are dynamic, changing over time. While variability is a natural aspect of these systems, it is also vital to define safe operating spaces, ensuring that critical ecological thresholds are not crossed or, alternatively, that social-ecological systems possess the resilience to adapt when reorganisation becomes inevitable and Holocene-like conditions are unfeasible. Establishing such ranges, that is, safe operating spaces, means either remaining within the Holocene range where feasible or within limits of adaptation where unfeasible. Drawing inspiration from Dearing et al. (2014) and aligning with Figure 1, the conceptual Figure 2 illustrates how a knowledge of variation throughout the Holocene informs the delineation of safe operating spaces and the potential for adaptation under future novel conditions.

In circumstances marked by high uncertainty, where the complexity of social-ecological systems intersect with the highly uncertain nature of climate change and its ramifications, a scenarios-based approach is appropriate. This involves envisioning different combinations of economic, climatic and social-ecological trajectories. Both probabilistic and exploratory approaches start from the present, moving into the future. The former forecasts the future from current empirical trends, while the latter extrapolates future policy scenarios from current sociopolitical positions. However, the weakness of both approaches lies in their rootedness in the present, leading to path dependency and resistance to transformative change beyond current realities. Exploratory future visioning, in contrast, often relies on scenario approaches that present a diversity of possible futures for assessment. Different options, with different varying levels of plausibility, can be discussed to support more informed decision-making. An example is the use of representative concentration pathways (RCPs) to explore the radiative effects of different scenarios of greenhouse gas emissions in 2100 (IPCC 2021). Scenario approaches are particularly useful for exploring the potential consequences of different policy choices. For instance, they could enlighten connections between different mitigation scenarios at the global level and the necessary adaptation at the local level. Scenarios can also be effective ways of elaborating contingency plans. In Figure 2, such scenarios can be identified by using exploration of future trajectories to identify various potential future positions of the system. For example, four possible scenarios include: (1) restoration of Holocene-like conditions; (2) emergence of a functional novel

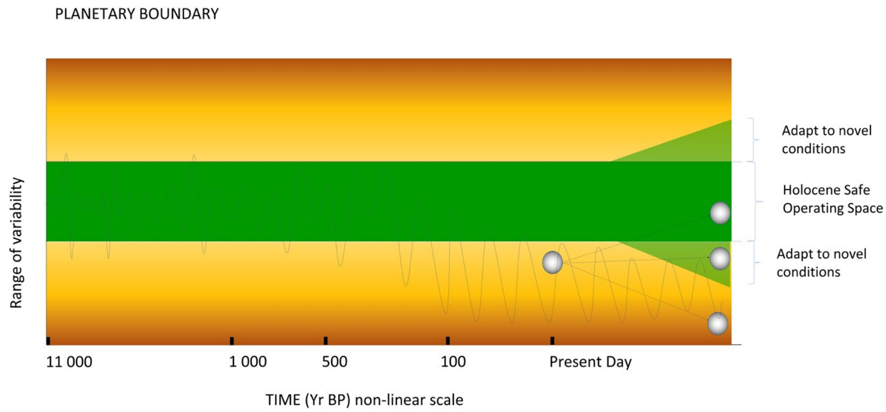

FIGURE 2 | Conceptual diagram showing how knowledge of variability throughout the Holocene could help inform safe operating spaces. The dark-green area shows the Holocene range of variability and the grey sphere shows present and future positions of the system, and dotted lines represent alternative trajectories. The safe operating space expands in the Anthropocene (shown in paler green) as we accept that Holocene conditions may no longer be feasible, in which case adaptation to novel conditions will be needed (after Dearing et al. 2014).

system (higher than Holocene); (3) emergence of a functional novel ecosystem (lower than Holocene); and (4) continued unsustainable trajectory. Such scenarios can be viewed through a resist/accept/direct (RAD) framework that allows stakeholders to integrate objective (what is the trajectory and can we change it) and subjective (do we find this trajectory desirable) management considerations (Higuera et al. 2022; Kariuki et al. 2021; Thomas et al. 2022).

4 | Quantitative Techniques to Apply the Conceptual Framework

4.1 | Time-Series Analysis to Detect Variation From the Mean State

A central premise underlying the PB concept is the acknowledgement that system state variables can undergo sudden and/or abrupt changes during the transition between distinct states, which may or may not coincide with the boundaries of safe operating spaces. In palaeoecological analyses, the identification of such transitions using 'Change-point' statistical detection methods has become common (Seddon et al. 2014; Blaauw, Christen, and Aquino-López 2020). Notably, classical distance-based approaches to detect abrupt changes or zones in multivariate datasets include multivariate regression trees and zonation, along with temporally constrained clustering methods (Gordon and Birks 1972).

Alternatively, methods borrowed from time-series analysis or linear regression type approaches have been adapted to individual palaeoecological state variables, for example, STARS algorithm (Rodionov 2004, 2006) and generalised nonlinear least squares (Carstensen and Weydmann 2012; Seddon et al. 2014). The application of generalised additive modelling (GAM) for state variables inferred from palaeoecological data has become a common tool for characterising the dynamics of long-term data and detecting significant trends within temporal sequences (Simpson 2018). The main advantage of GAMs lies in their absence of prior assumptions about the system trends, allowing flexibility in modelling linear, curvilinear or abrupt trends. Moreover, the generalised modelling framework allows the application of these models to various state variables (e.g., ordination axes, quantitative estimates of a state variable, and proportion data). Importantly, these approaches require no standardisation of the sample resolution and so bypass the common limitation of palaeoecological data with its unevenly spaced samples. Additionally, hierarchical GAMs facilitate simultaneous analyses of multiple-state variables within the same model (Bhatta et al. 2023).

4.2 | Estimations of Rates of Change

An alternative approach for detecting changes in means of a given state variable is to characterise shorter-term deviations from mean state. Rate of change analysis is commonly employed in palaeoecological analysis, evaluating the rate of change in a univariate state variable, or the rate of change in a dissimilarity metric (in the case of multivariate data) between subsequent samples (Mottl, Grytes, et al. 2021). The key advantage of this approach lies in the ability to highlight short-term fluctuations that might not be detected by time-series modelling approaches such as GAMs.

However, the disadvantage of rate of change analyses is its inherent sensitivity to noisy variation when comparing sample to sample. To address this, on a single site, a control mechanism involves creating a distribution of sample-to-sample differences and then selecting a threshold above which abrupt change has occurred (Seddon, Macias-Fauria, and Willis 2015). Employing this method across multiple sites allows for an assessment of the regional synchronicity in responses, providing further evidence of deviations in mean (Mottl, Grytes, et al. 2021).

Furthermore, rates of change can be aggregated at larger scales, such as the continental scale. This allows the utilisation of site-based estimates of rates of change to address broad-scale issues related to the PB (see the scaling section below). For example, Mottl, Flantua, et al. (2021) aggregated rates of change estimates for over 1000 pollen sequences spanning four different continents revealing a consistent increase in rates of change for the last 3000 years compared to the mid-Holocene levels (Mottl, Flantua, et al. 2021). This approach demonstrates the potential for upscaling site-based indices of fine-scale changes to the larger scales relevant for identifying PB.

4.3 | Indicators of Resilience

Indicators of resilience are crucial in assessing ecosystems under stress, as reduced resilience may heighten the likelihood of abrupt system change across thresholds. Identifying a declining trend in resilience can, therefore, offer insight into the proximity of safe–unsafe boundaries. The conventional approach involves identifying metrics in time series that exhibit evidence of critical slowing down or flickering between alternate states, such as autoregressive correlations and variance (Scheffer et al. 2012).

Nevertheless, attempts to identify these metrics in palaeoecological data encounter challenges, including appropriate selection of proxies for whole system behaviour, sample resolution and unequal time increments (Wang et al. 2012). Alternative approaches have sought to use palaeoecological data to provide evidence of the changes in the system's structural dynamics accompanying resilience. Examples include assessing aquatic community behaviour and interactions (Doncaster et al. 2016; Wang et al. 2019; Mayfield et al. 2020, 2021, 2022) and the balance of feedback mechanisms (Wang, Dearing, and Langdon 2022). These alternative methodologies contribute to a more comprehensive understanding of resilience indicators in palaeoecological contexts.

5 | Case Studies

In order to explore the interface between palaeoecological data and safe operating spaces, we have selected three case studies for our preliminary exploration. The case studies are areas where there has been extensive palaeoecological work, and where the data have shown evidence of deviation from historical ranges of variability and/or possible threshold behaviour. Each case study is required to answer the following questions to make predictions more robust and comparable:

1. How to identify ecological transitions using palaeodata, determine the momentum of change and acknowledge historical perspectives?
2. How are ecosystem services impacted and what management strategies can be employed to mitigate?
3. How to define the safe operating space that could contribute to delineating PB?

We have identified three case study areas, the Western Cape of South Africa, Taihu Lake, China, and the Murray–Darling Basin, Australia. These three cases represent distinct socioeconomic and biophysical systems, yet all are closely linked to the three key PB of pollution, biodiversity loss and climate change. Taihu Lake, located in the Yangtze River Delta, exemplifies an intensely modified environment shaped by rapid urbanisation and industrialisation within a highly dynamic delta region. In contrast, the Western Cape is part of the Cape Floristic Region, a landscape that has sustained human interactions for millennia but with lower intensity, in a megadiverse area that supports Fynbos and Afromontane forests. Finally, the Murray–Darling Basin illustrates the complex challenges of water scarcity and flood management in a heavily regulated catchment, highlighting the interplay between human interventions and natural hydrological processes. For all of these case studies, we have comprehensive data and expert knowledge, providing ideal test cases for applying the quantitative methods described above and for developing methods that integrate data from multiple sites to upscale between landscape-level and regional studies.

5.1 | Western Cape, South Africa

The Western Cape of South Africa (Figure 3) is a megadiverse area that is important for numerous ecosystem services including water, biodiversity and recreation. The area experiences a Mediterranean-type climate with rainfall concentrated mostly in the winter months to the west and more evenly distributed moving eastwards along the coastline (year-round rainfall) (Hobbs, Lindesay, and Bridgman 1998). It is topographically diverse and contains numerous wetlands that are important for biodiversity, water provision, recreation and fisheries. The Cape Fold mountains provide an important source of water supply to the populace through orographic uplift. Although the area has a long history of human occupation (Cowling 2018), their influence was relatively light until the past several centuries with urbanisation, agriculture, water abstraction and forestry transforming the landscapes surrounding vleis (wetlands) over the past 300 years, leading to run-off, erosion and pollution (Anderson and O'Farrell 2012). The current population is concentrated in large conurbations including Cape Town, although much of the populace is rural and lives in villages or smaller towns. Changes in moisture availability and sea-level rise, as well as changes in land use are likely to affect numerous ecosystem services. Studying the effects of past sea levels and climate change, as well as the history of land use, can help in exploring future scenarios of change and identifying potential tipping points. Here, we examine two sites that are ideal candidates to examine the 'climate change' and 'Freshwater consumption and the global hydrological cycle' PB (Rockström et al. 2009a, 2009b; Steffen, Richardson, et al. 2015; Steffen, Broadgate, et al. 2015). Both systems have crossed over thresholds in the most recent past. Climate is the primary driver at Princessvlei (Figure 3A,B) during the late Holocene, while marine-driven changes are more evident at Eilandvlei since the mid-Holocene (Figure 3C,D). We will conduct quantitative analyses to identify transitions between marine and freshwater states and explore the interplay between changing climate and sea-level rise. Specifically, we will review and synthesise diatom data to test these impacts. These analyses will help us project future scenarios of ecosystem service provision under various combinations of climate change and sea-level rise.

Princessvlei is a permanent, alkaline, eutrophic, freshwater coastal lake (Harding 1992; Harrison 1962) that lies in an interdunal depression encroached on by high-density residential, industrial and agricultural land uses (Figure 3A). Princessvlei holds centuries of historical and cultural significance. It has served the local community as a recreational area and baptism site (Anderson, Avlonitis, and Ernstson 2014), and was one of the few natural areas accessible to marginalised groups under

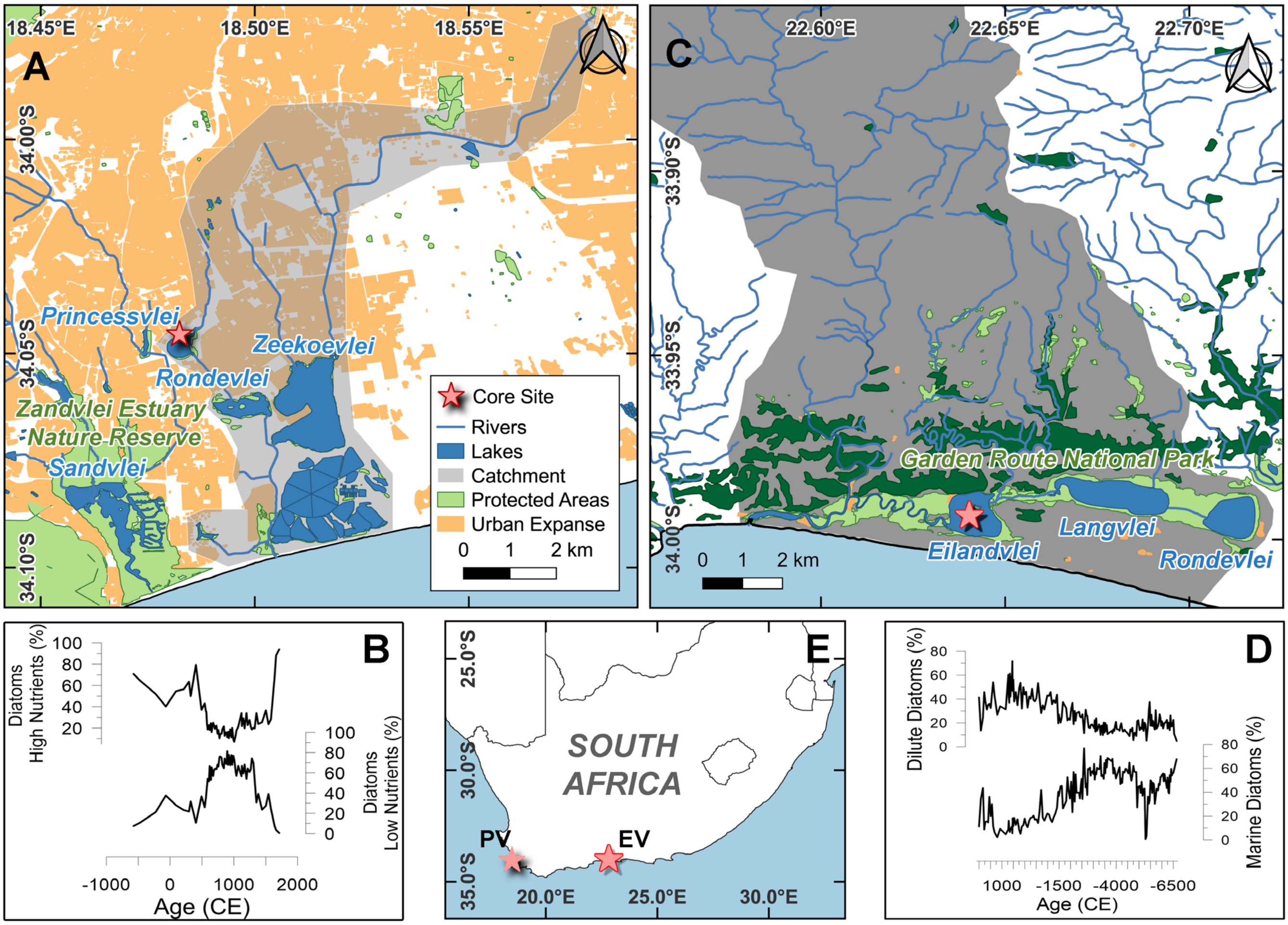

FIGURE 3 | (A) The Princessvlei (PV) catchment is located on the Cape Flats, (B) the percentage abundance of PV diatoms based on nutrient requirements over the last 2600 years, (C) Eilandvlei (EV) is part of the Wilderness Complex, (D) the percentage abundance of EV diatoms based on salinity preferences over the last 8000 years and (E) both sites are located in South Africa. Map lines delineate study areas and do not necessarily depict accepted national boundaries. Data from Kirsten et al. (2018) and Kirsten and Meadows (2016).

Apartheid (Ernstson 2014). It also has ties to the indigenous Khoisan history. A recent study reveals Princessvlei's ability to assimilate ammonium nitrogen, improving water quality (Underhill 2017). Civic interventions have been working on rehabilitating the wetland and Fynbos, leading to increased bird life, pollinator activity and potential plant diversity similar to professionally managed sites (Anderson, Avlonitis, and Ernstson 2014; Scientific Aquatic Services 2020).

Unconsolidated sand dominates most of the area, originating from river and wind erosion and deposition, with increased transport during periods of summer aridity and anomalously high southerly wind velocities (Harris, Oom, and Diamond 1999; Roberts et al. 2009). Human activities become apparent in the palaeoecological record after 600 cal year BP when a rise in representation of coprophilous spores suggests the prevalence of livestock, alongside changes in vegetation composition (Cordova et al. 2019). Although humans would have been present in the landscape for millennia (Orton et al. 2020), the record suggests increasing human impact from this time. In the last 300 years, the site has experienced a reduction in biodiversity, an introduction of exotic flora, fire suppression and a decline in herding activities that coincides with the European settlement period (Marais 2019; Neumann, Scott, and Bamford 2011). Overall, the record reveals an interplay between the relative dominance of the westerly belt and the South Atlantic high-pressure cell in determining the hydroclimate of the lake, and a later influence of human land use that has shifted the system towards a eutrophic state irrespective of moisture availability.

Climate projections suggest that increased extreme climate events are likely to put stress on our natural resources (Masson-Delmotte et al. 2021), with the southwestern Cape likely to experience greater deficits in moisture availability. In the future, in response to a warmer and drier climate and more intensive land use, we anticipate a dominance of the eutrophic state due to increased human activities within the catchment and higher human demands on the system. The canalisation of much of the catchment limits the ability of the system to assimilate pollutants, which suggests that Princessvlei will likely become a sink for pollutants. This is likely in contrast to the natural functioning of the system solely under climate change, where catchment supply and surface runoff are restrained to high-impact, short-interval events (Underhill 2018). This would cause oligotrophic groundwater to become the primary source of water for the system, leading to a decline in open water conditions and biodiversity.

Eilandvlei, situated in the Wilderness Embayment on the southern Cape coastal plain of South Africa (Figure 3C), is one of three coastal lakes which make up the Wilderness Lakecomplex (Illenberger 1996; Martin 1956; Martin 1962), part of the Wilderness National Park (Hart 1995; Randall 1995). The complex is culturally significant and hosts diverse terrestrial, freshwater, estuarine and marine species (Olds et al. 2016). Primary activities within the catchment are forestry and agriculture, which have transformed nearly 50% of the land (Russell 1999). Tourism and recreation are increasingly vital to the local economy (Allanson and Whitfield 1983; Olds et al. 2016). The Wilderness Lake complex regulates flood and nutrient levels (Russell et al. 2012) and supports human activities such as freshwater abstraction, fishing, bait collection and intensive recreational use, with artificial breaching due to low-lying developments. The southern Cape is particularly dynamic as it is influenced by both temperate and tropical circulation systems, that is, it receives both winter rainfall from the westerlies and summer rainfall from the influence of the ITCZ, leading to year-round rainfall and high rainfall variability (Quick et al. 2018). The Wilderness Embayment and neighbouring Swartvlei systems are the only marine-connected, warm-temperate coastal lakes along the South African coast and are sensitive to changes in sea level (Wündsch et al. 2018). A projected sea level rise of 0.5–1.5 m by 2100 as a result of climate change (Allison, Palmer, and Haigh 2022) will have immense impacts on Eilandvlei and Wilderness Lake complex. The deeper penetration of warm, ocean water would likely lead to a marine-dominated system, over the current fresh brackish to brackish system (Russell 2013). This will lead to changes in species composition, ecosystem functionality, habitat availability, increased sedimentation, loss in biodiversity and a decline in sediment and water quality. Storm surges coupled with high astronomical tides increase the susceptibility of the coastline to erosion and land loss, as well as change the water chemistry of coastal systems. The southern Cape coast is highly susceptible to large swells along its wave-dominated coastline, and under increased stormy conditions, this can lead to changes in physical processes and biological responses with an ultimate impact on ecosystem services.

These case studies will be relevant to the freshwater use, biosphere integrity and land system change PB, providing information relevant to management of water quality and salinity and the interacting effects of changing land use and climate. The range of variability observed through the Holocene as well as the more recent effects of intensified land use might help to explore future scenarios of water quality and biodiversity under different combinations of land use, climate and sea-level rise.

5.2 | Taihu Lake, China

Lake Taihu (Figure 4) ranks as China's third largest freshwater lake, covering an area of 2338.1 km^2, is located within the highly urbanised (> 40 million inhabitants) and agricultural catchment (36,500 km^2) in the Yangtze River Delta region (Qin et al. 2019). The lake provides critical ecosystem services that support the livelihoods of millions of people residing in the basin, including freshwater, food, aesthetic and spiritual values, flood and drought regulation and biodiversity conservation. Humans have modified lake ecosystems in this region for millennia, but recent industrialisation and urbanisation have led to an exponential increase in anthropogenic activities and resource utilisation (Ellis and Wang 1997; Xu et al. 2015).

The Taihu lakes serve as a forewarning of the environmental changes unfolding in China, and have suffered severe degradation (Qin et al. 2019). The Taihu Lake basin has experienced the most dramatic social and economic transitions since the 1980s, with remarkable economic growth (annual GDP growth rate of 15.7%), population expansion (annual growth rate of 3.0%), urbanisation (annual growth rate of 9.2%) and

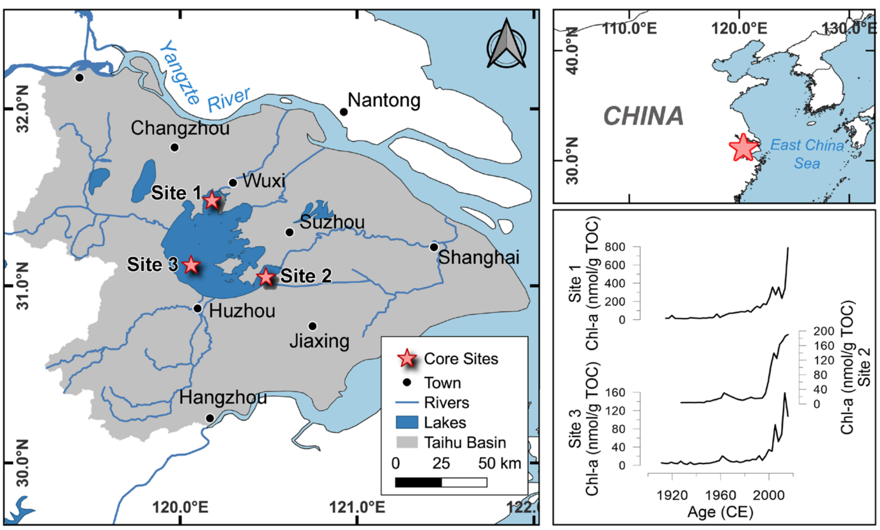

FIGURE 4 | Sketch map of the Taihu Lake Basin in the Yangtze River Delta, East China, with the locations of sediment core sampling sites (site 1, site 2, site 3). The inset in the bottom right corner presents the chlorophyll-*a* (Chl*a*) concentration results for each site over the past century, derived from sediment pigment analysis. Map lines delineate study areas and do not necessarily depict accepted national boundaries. Data from Lin et al. (2021).

intensive industrialisation (Xu et al. 2016). The increasing eutrophication of the lake has resulted in several adverse impacts, including harmful algal blooms, increased frequency of anoxic events and fish mortality (Zhang et al. 2016), leading to a substantial decline in the provision of ecosystem services (Lin et al. 2023). The degradation of the lake has also caused biodiversity loss, ecological service disruption and environmental disasters. A significant example occurred in May 2007 when a massive algal bloom impacted the lake's water treatment facilities, causing a highly publicised crisis that left millions of residents without potable water for nearly a week (Guo 2007). This kind of event has posed great threats to ecological security and regional sustainable development.

The Lake Taihu ecological crisis has served as a rallying point for the establishment of an intensive lake restoration programme. Billions of dollars have been allocated towards lake ecosystem restoration through environmental protection actions. However, local strategies aimed at protecting and restoring lake ecosystems have largely failed to halt or reverse the regional-scale decline (Qin et al. 2019). Although progress has advanced considerably regarding changes in the Taihu Lake ecosystem, most studies mainly focus on recent 'symptoms' of the problems rather than their deep historical causes (Lin et al. 2019; Xu et al. 2017).

We review and synthesise a large body of published palaeorecords to identify the critical transition points in Taihu Lake's ecosystem over the past century. This includes analysing various proxies, such as mass magnetic susceptibility, metal elements, total phosphorus and nitrogen, organic carbon, nutrient stoichiometry, pollen and macrophytes, eDNA, pigment, aliphatic hydrocarbons and cyanotoxins. By comparing the different proxies across sediment cores obtained from various parts of the lake, we can identify the onset and intensity of eutrophication, contamination histories and changes in the algal community. Furthermore, we will quantify historical variability and an Anthropocene baseline for Taihu Lake basin to establish a reference point for restoration efforts and to inform delineation of a safe and just operating space for Taihu Social-Ecological Systems from a long-term perspective.

Additionally, by comparing proxies with historical records of human activities, such as population growth, land use change and industrialisation, we aim to establish a baseline condition before human disturbance and assess the degree of deviation from the historical condition. By analysing the trade-offs and synergies between environmental sustainability and socio-economic development, we aim to establish a set of environmental and social limits for Taihu SES that would allow for sustainable management and equitable distribution of benefits. The findings from this study will not only guide restoration efforts and inform policy decisions aimed at achieving sustainable management of the lake basin but also contribute significantly to the global comprehension of PB, especially for freshwater security.

5.3 | Murray–Darling Basin, Australia

The Murray River (MDB) is Australia's food bowl generating AUD40B p.a. in agricultural production. This is largely based on intensive irrigation agriculture which began in the late 19th Century. Intensive horticulture and dairying were supported by the abstraction of much of the natural river flow of the Murray River and the establishment of a network of impoundments, mostly from the 1920s. The Murray River (Figure 5) has been subject to anthropogenic stressors for over 170 years, with testimony to the impact of gold mining in the tributaries and domestic and stock waste presented to the Royal Commission into the state of the waters by 1900 (Davis, Murray, and Burchell 1902). Dryland and irrigation salinisation resulted from tree clearance and water use and this impacted heavily from the 1970s (Macumber 1991) and, by the early 21st century, the system was widely recognised as being degraded (Norris et al. 2001). Recently, the Darling River has suffered under severe drought, exacerbated by floodplain harvesting, whereby cotton farmers divert flood waters into

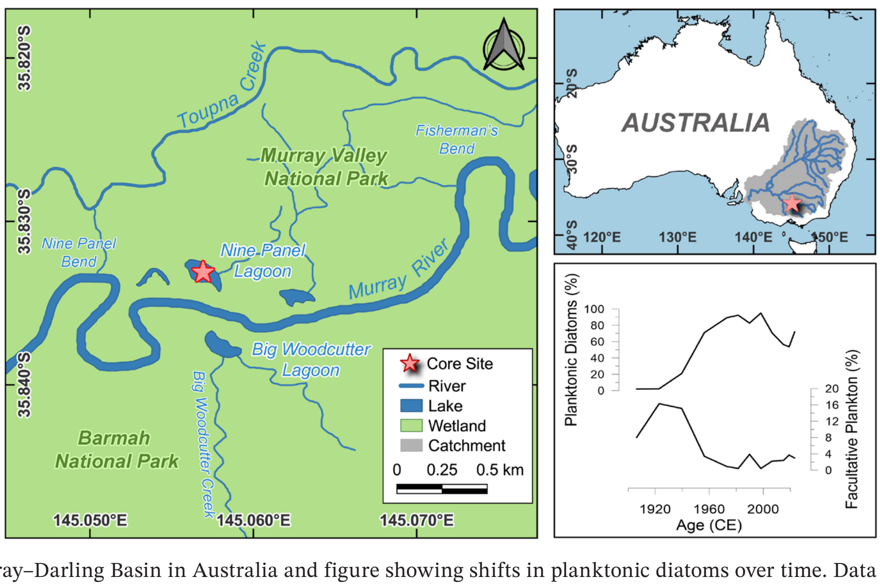

FIGURE 5 | The Murray–Darling Basin in Australia and figure showing shifts in planktonic diatoms over time. Data from Map lines delineate study areas and do not necessarily depict accepted national boundaries. Data from Gell (2024).

extensive off-river storages, denying the river flushing flows. Since 2019, there have been several kills of over a million fish with anoxia and high ammonia concentrations to blame (Jackson and Head 2020).

For restoration, the main focus has been on the return of environmental flows and this has culminated in the Murray–Darling Basin Plan (Commonwealth of Australia 2012) that is charged with returning flow to the system through a Cap on water abstractions, and the separation of water and land as property, enabling water to be traded in a cap-and-trade market. The shifting value of commodities has seen water allocated in humid upstream zones for dairying and directed to arid downstream zones for almonds. This has created extreme conflict leading to rural communities rallying in the nation's capital and the management authority being subject to class actions. The transfer of water is limited by constraints on allowing rivers to flow overbank and flood private land and high flows are eroding river banks exacerbating sediment pollution. There is strong support for the use of environmental flows to remedy the widespread degradation of the system. There remains a strong push to ease constraints to flooding to enable watering of downstream wetlands and floodplains for ecological recovery (Pittock et al. 2023).

While understanding of the connections between hydrology and ecology of the floodplain wetlands has mostly drawn on evidence from monitoring, the Murray System has been the focus of extensive palaeolimnological research that has inferred the changing state of wetlands over several thousand years. Over 60 sites have been examined (Figure 5) and the records from these testify to increased pollutant loads, mostly since regulation in the 1930s but also from as early as the 1880s (Gell and Reid 2016). No studied wetland has escaped the impact of European settlement, with 80% impacted by sediment, 48% by nutrients and 34% by salinisation (Davies and Lawrence 2019; Gell and Reid 2014). There is evidence for the widespread replacement of submerged aquatic plants (Reid et al. 2007) as well as shifts in diatom algae, microfauna and the abundance of small-bodied fish (Gell, Mills, and Grundell 2012; Grundell et al. 2012; Humphries 2007; Jensen 2002; Kattel, Dong, and Yang 2014).

Palaeoecological approaches can reveal these changes and can place modern data in context. The benefit of this longer-term perspective includes the capacity to understand the influence of low-frequency cycles, to identify past critical transitions in state that may preclude restoration, to understand natural baseline conditions (Finlayson et al. 2017) and to better understand the trajectory of change (Gell, Perga, and Finlayson 2018). The long-term record offers the prospect of better understanding the range of conditions wetlands have experienced and so their inherent level of resilience and limits of acceptable change (Gell 2019). Under scenarios of reduced rainfall and runoff, in a Basin where water allocations to irrigation are being recovered for environmental purposes, the long-term record can guide adaptation of freshwater management and land use where restoration to precolonial conditions is no longer feasible.

6 | Scaling Between Landscape Assessments and PB

6.1 | Scaling

Understanding the Earth's limits at the planetary scale is vital for long-term sustainability planning. However, the Earth's heterogeneity in resources and land use demands a nuanced approach (Häyhä et al. 2016). PB, by definition global in scale, impose constraints on processes that occur at smaller scales, and conversely, the aggregation of small-scale processes can impact global-scale phenomena (Hughes et al. 2013; McLaughlin 2018). While measuring changes in PB parameters, information gathered at smaller scales must be amalgamated, leading to loss of place-specific details and experiences of resource scarcity. Moreover, sustainability initiatives can be operationalised at various scales—subnational, national, regional, continental and global (Dearing et al. 2014; Häyhä et al. 2016; McLaughlin 2018). Although global targets and boundaries may be defined, it is usually at national levels that policies are formulated and management interventions are typically implemented at landscape and local scales (Turner and Wills 2022).

Scaling presents different challenges for different boundaries. The differentiation made by Rockström et al. (2009a, 2009b) between top-down processes (e.g., climate change) and bottom-up processes (e.g., freshwater use) underscores the complex interplay between global and local dynamics (Rockström et al. 2009a, 2009b) and the need to consider both scaling down of PB for local and national implementation and scaling up of local and national data to amalgamate heterogeneity at the planetary scale.

6.2 | Driving Forces–Pressures–States–Impact–Response (DPSIR) Framework

The DPSIR framework has proved helpful in downscaling PB to regional levels (Nykvist, Persson, and Persson 2013; Häyhä et al. 2016; McLaughlin 2018). The rationale for using a DPSIR framework is that humans can only control drivers and pressures (e.g., pollution, nitrogen deposition and land use change), whereas some PB are states (e.g., stratospheric ozone depletion and climate change) or impacts (biodiversity loss).

Applying the DPSIR framework, Nykvist, Persson, and Persson (2013) elucidated causal linkages between drivers/pressures and states/impacts, for example, a change in land use such as conversion of forest to cropland could lead to biodiversity loss. Nykvist et al. then defined safe boundaries for drivers and pressures (nitrogen, phosphorus, freshwater use and pollution), states (ozone depletion, climate change, ocean acidification, aerosol loading and land use change) and an impact (biodiversity loss) (Nykvist, Persson, and Persson 2013). Such limits can then be translated to national (Nykvist, Persson, and Persson 2013; Cole, Bailey, and New 2014) and subnational scales (McLaughlin 2018). In a similar downscaling exercise, Cole, Bailey, and New (2014) developed a barometer that indicates whether South Africa is within a safe operating space for key environmental variables. In order to evaluate boundaries at a national scale, Cole et al. made several modifications to the PB. Even with these modifications, Cole et al. caution that local stresses and impacts might be lost when data are aggregated at the national level. This becomes especially relevant when human dimensions such as food security and water access are assessed (Cole, Bailey, and New 2014).

Cole, Bailey, and New (2014) further refined the distinction between top-down and bottom-up processes, categorising inherently global boundaries (Type A, e.g., climate change and ozone depletion), national limits (Type B, e.g., land use change and freshwater resource) and those combining local and national thresholds (Type C, e.g., phosphorus concentrations or biodiversity loss) 2 (Cole, Bailey, and New 2014). Nykvist, Persson, and Persson (2013) contend that top-down or Type A boundaries need to be converted to a corresponding pressure (e.g., greenhouse gas emission) that can be quantified at a global scale and governed at a national scale, taking into account different burdens, responsibilities and capacities (Häyhä et al. 2016; Turner and Wills 2022).

At a subnational scale, McLaughlin (2018) developed regional analogues for PB and applied the DPSIR framework. Results showed that only one, freshwater use could be restored rapidly to within its safe operating space, while the others would require more gradual manipulation if irreversible degradation or nonlinear declines in ecosystem functions were to be avoided. In all cases, societal willingness to respond was essential. A positive example of this is the Lummi water rights settlement initiative, which takes a more holistic approach including riparian habitat restoration, in-stream flow requirements and water quality—thereby addressing several of the indicator variables outlined above (McLaughlin 2018).

Assessing local resource scarcity and vulnerability is imperative, necessitating a comprehensive examination that incorporates critical loads and ecological hotspots into policy formulation and practical application. The challenge extends beyond recognising dynamic interactions between scales; it involves developing a methodology for upscaling that accommodates inherent variations in analytical approaches. Attaining a thorough understanding of PB demands a holistic strategy bridging the gap between global imperatives and local intricacies. In this context, the pivotal integration of local and global perspectives comes to the fore. Local thresholds (safe operating spaces) embody a nuanced grasp of resource availability, ecological resilience and vulnerability, thereby facilitating precise policies and interventions at smaller scales. In contrast, PB represent overarching global benchmarks, delineating limits on critical global-scale processes crucial for maintaining Earth's equilibrium. This dual framework emphasises the imperative for a seamless methodology in upscaling assessments, ensuring that local intricacies contribute significantly to the global comprehension of planetary limits and, consequently, fostering strategies for sustainable resource management.

7 | Monitoring Progress

Methodologies are needed for monitoring progress and continued re-evaluation of safe operating spaces. Monitoring techniques including satellite remote sensing can assist in tracking degradation over recent decades and informing restoration that considers changes that have occurred since the 1980s. Such information can be especially valuable in tracking rates of recent changes, including changes in population size and distribution and in monitoring the impact of and recovery from extreme events (e.g., droughts, fires and floods). Knowledge of these trajectories can assist in making predictions of how such events may impact social-ecological systems in the future. (e.g., recurrent events such as El Niño, La Niña and increasing occurrence of intense wildfires.) A scaled approach that integrates local knowledge and national policy goals with global boundaries can realise the synergy among long-term data, landscape management and the PB community. It will assist in planning for new ideas on transition pathways integrated with the sustainable development goals.

The concept that operating spaces should be not only safe but just has been integral to the PB literature since Raworth et al.'s 'doughnut', which considered not only the safe environmental limits but also the minimum requirements for human well-being (Raworth 2012; Turner and Wills 2022). It was more recently developed into a combined index that included both safe boundaries for maintaining Earth system resilience as well as safeguarding future generations against significant harm (Rockström et al. 2023). In a comparison of over 60 countries, Nykvist et al. noted that it was the highly developed countries and some emerging economies that most frequently transgressed boundaries (Nykvist, Persson, and Persson 2013). Similarly, in an analysis of 149 countries, Zhang et al. (2023) compared sustainable and natural parameters related to the PB, as well as the rate and direction of change in these parameters over a 20-year timeframe (Zhang et al. 2023). They concluded that high-income countries in general had high and increasing capacity for SD but had low capacity for nature. The results reflect Kuznets curve, where rapid development is accompanied by increasing demand for human well-being, while postindustrial countries face few environmental pressures and thus appear to have better capacity for sustainable development, but low nature capacity as much biodiversity is already lost or transformed (Zhang et al. 2023). This approach also hides the fact that wealthy countries can externalise their environmental impact through international trade while highly polluting industries tend to be located in areas where labour is cheaper (Häyhä et al. 2016). This can be resolved by adopting a 'footprint' approach that considers the environmental impact of consumption both inside and outside a territory (Hoff, Nykvist, and Carson 2014; Dao et al. 2015), for example, the carbon footprint assesses the total carbon emissions for an entire product life cycle (Häyhä et al. 2016).

8 | Conclusions

There is a potential synergy between landscape analysis at a range of scales and the PB literature. Using palaeoecological techniques and other long-term data, we aim to chart change in key parameters including land system change, biosphere integrity, freshwater and biogeochemical flows over timescales of decades to millennia, potentially covering the whole of the Holocene as a reference period, although shorter timescales are also relevant. We aim to interpret these changes using a complex systems approach that considers environmental, biotic, social and historical factors. By describing and modelling change over long-time periods, we aim to contribute to mapping sustainable trajectories that stabilise essential Earth system processes and associated ecosystem services or guide adaptation when novel conditions are inevitable. As part of this process, we have outlined quantitative methods for detecting tipping points in time-series data and exploring the drivers that cause transitions between stable states. We explore the synergy between landscape analysis at a range of scales and the PB literature and aim to help define and chart the pathways towards safe operating spaces and adaptation to novel conditions. This position paper carries key messages that will shape the progression of our work.

First, a time-series approach is important in defining how far the current state system has diverged from its Holocene-like range of variability, and how close it may be to a potentially dangerous tipping point (Dearing et al. 2014). This understanding is critical in defining safe operating spaces (see Figure 2) and also in identifying when return to Holocene-like conditions is impossible. The application of the resist–accept–direct framework to decision-making can help in distinguishing when intervention, acceptance or adaptation is required.

Second, in order to best realise the synergy between palaeoecology and PB, there is a need to aggregate from our case studies to national, regional and global scales. Scaling up to planetary or regional scales may be possible through aggregation of subnational and regional case studies, however, it should be noted that such an exercise is likely to obscure the local experience of resource scarcity, climate change, lack of fresh water or pollution. But equally, regional and local-scale studies assist in defining national targets for pressures and drivers.

Third, quantitative approaches to analyses of time-series data are essential in operationalising the PB concepts in order to consider tipping points in ecological and social-ecological systems. Such tipping points may differ between locations, again emphasising the need for smaller-scale perspectives associated with particular locations and means of operationalising global PB at national and subnational levels.

Fourth, the 'driving forces-pressures-states-impact-response' (DPSIR) framework is useful in exploring the drivers and pressures that lead to state system change, for example, biodiversity loss (Nykvist, Persson, and Persson 2013; Häyhä et al. 2016; McLaughlin 2018). It will be part of our work to analyse Dearing's ecosystem services indicators in a DPSIR framework (Dearing et al. 2012). The distinction between drivers, responders and impacts is important because it is the drivers and pressures which can be managed. National or subnational boundaries, for example, on emissions, first identify the drivers and pressures that, when aggregated, impact the global state.

Fifth, a return to past conditions is unlikely for many locations and adaptations to novel scenarios will be essential in many cases. Using a resist—accept—direct framework can assist stakeholders in deciding how to respond to alternative possible futures.

Author Contributions

Lindsey Gillson: conceptualization, project administration, visualization, writing – original draft, writing – review and editing. **Alistair Seddon:** conceptualization, writing – original draft, writing – review and editing. **Ondřej Mottl:** conceptualization, writing – original draft. **Kelly Kirsten:** conceptualization, project administration, writing – original draft. **Peter Gell:** writing – original draft. **Rob A. Marchant:** writing – original draft, writing – review and editing. **Christoph Schwörer:** conceptualization, writing – review and editing. **Estelle Razanatsoa:** writing – review and editing. **Paul J. Lane:** writing – review and editing. **Colin J. Courtney-Mustaphi:** writing – review and editing. **John Dearing:** conceptualization, writing – original draft, writing – review and editing. **Ke Zhang:** conceptualization, writing – original draft.

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Conflicts of Interest

The authors declare no conflicts of interests.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

References

Allanson, B. R., and A. K. Whitfield. 1983. "Limnology of the Touw River Floodplain." 0798829621, Cooperative Scientific Programmes, CSIR.

Allison, L. C., M. D. Palmer, and I. D. Haigh. 2022. "Projections of 21st Century Sea Level Rise for the Coast of South Africa." *Environmental Research Communications* 4, no. 2: 025001. https://doi.org/10.1088/2515-7620/ac4a90.

Anderson, P. M. L., G. Avlonitis, and H. Ernstson. 2014. "Ecological Outcomes of Civic and Expert-Led Urban Greening Projects Using Indigenous Plant Species in Cape Town, South Africa." *Landscape and Urban Planning* 127: 104–113. https://doi.org/10.1016/j.landurbplan.2014.03.007.

Anderson, P. M. L., and P. J. O. O'Farrell. 2012. "An Ecological View of the History of the Establishment of the City of Cape Town." *Ecology and Society* 17, no. 3: 28–39.

Bhatta, K. P., O. Mottl, V. A. Felde, et al. 2023. "Exploring Spatio-Temporal Patterns of Palynological Changes in Asia During the Holocene." *Frontiers in Ecology and Evolution* 11: 1115784.

Biggs, H., S. Ferreira, S. Freitag-Ronaldson, and R. Grant-Biggs. 2011. "Taking Stock After a Decade: Does the 'Thresholds of Potential Concern' Concept Need a Socioecological Revamp?" *Koedoe* 53: 60–68.

Birks, H. J. B. 2012. "Ecological Palaeoecology and Conservation Biology: Controversies, Challenges, and Compromises." *International Journal of Biodiversity Science, Ecosystem Services and Management* 8, no. 4: 292–304.

Blaauw, M., J. A. Christen, and M. A. Aquino-López. 2020. "A Review of Statistics in Palaeoenvironmental Research." *Journal of Agricultural, Biological and Environmental Statistics* 25: 17–31.

Bourman, R. P., C. V. Murray-Wallace, C. Wilson, et al. 2022. "Holocene Freshwater History of the Lower River Murray and Its Terminal

Lakes, Alexandrina and Albert, South Australia, and Its Relevance to Contemporary Environmental Management." *Australian Journal of Earth Sciences* 69, no. 5: 605–629.

Braje, T. J. 2024. *Understanding Imperiled Earth: How Archaeology and Human History Can Inform Our Planet's Future*. Washington, DC: Smithsonian Institution.

Braje, T. J., and M. Lauer. 2020. "A Meaningful Anthropocene?: Golden Spikes, Transitions, Boundary Objects, and Anthropogenic Seascapes." *Sustainability* 12, no. 16: 6459.

Brewington, S., M. Hicks, Á. Edwald, et al. 2015. "Islands of Change vs. Islands of Disaster: Managing Pigs and Birds in the Anthropocene of the North Atlantic." *Holocene* 25, no. 10: 1676–1684. https://doi.org/10.1177/0959683615591714.

Carstensen, J., and A. Weydmann. 2012. "Tipping Points in the Arctic: Eyeballing or Statistical Significance?" *Ambio* 41: 34–43.

Cole, M. J., R. M. Bailey, and M. G. New. 2014. "Tracking Sustainable Development With a National Barometer for South Africa Using a Downscaled "Safe and Just Space" Framework." *Proceedings of the National Academy of Sciences* 111: E4399–E4408.

Commonwealth of Australia. 2012. "Water Act 2007 – Basin Plan 2012." Compilation No. 2 (24 November 2016). https://www.legislation.gov.au/Details/F2017C00078.

Cooper, G. S., and J. A. Dearing. 2019. "Modelling Future Safe and Just Operating Spaces in Regional Social-Ecological Systems." *Science of the Total Environment* 651: 2105–2117. https://doi.org/10.1016/j.scitotenv.2018.10.118.

Cordova, C. E., K. L. Kirsten, L. Scott, M. Meadows, and A. Lücke. 2019. "Multi-Proxy Evidence of Late-Holocene Paleoenvironmental Change at Princessvlei, South Africa: The Effects of Fire, Herbivores, and Humans." *Quaternary Science Reviews* 221: 105896. https://doi.org/10.1016/j.quascirev.2019.105896.

Cowling, R. 2018. "The Palaeo-Agulhas Plain-An Ice-Age Refuge for *Homo sapiens*." *Quest* 14: 10–13.

Dao, H., D. Friot, P. Peduzzi, B. Chatenoux, A. De Bono, and S. Schwarzer. 2015. *Environmental Limits and Swiss Footprints Based on Planetary Boundaries*. Geneva, Switzerland: UNEP/GRID-Geneva and University of Geneva.

Davies, P., and S. Lawrence. 2019. "Engineered Landscapes of the Southern Murray–Darling Basin: Anthropocene Archaeology in Australia." *Anthropocene Review* 6: 179–206.

Davis, J., S. Murray, and F. N. Burchell. 1902. "Interstate Royal Commission on the River Murray, Representing the States of New South Wales, Victoria, and South Australia: Report of the Commissioners. With Minutes of Evidence, Appendices, and Plans." Sands and McDougall Limited, Printers.

Dearing, J. A. 2006. "Climate-Human-Environment Interactions: Resolving Our Past." *Climate of the Past* 2: 187–203.

Dearing, J. A., R. W. Battarbee, R. Dikau, I. Larocque, and F. Oldfield. 2006. "Human-Environment Interactions: Learning From the Past." *Regional Environmental Change* 6: 1–16. https://doi.org/10.1007/s10113-005-0011-8.

Dearing, J. A., R. Wang, K. Zhang, et al. 2014. "Safe and Just Operating Spaces for Regional Social-Ecological Systems." *Global Environmental Change* 28: 227–238.

Dearing, J. A., X. Yang, X. Dong, et al. 2012. "Extending the Timescale and Range of Ecosystem Services Through Paleoenvironmental Analyses, Exemplified in the Lower Yangtze Basin." *Proceedings of the National Academy of Sciences* 109: E1111–E1120.

Doncaster, C. P., V. A. Chávez, C. Viguier, et al. 2016. "Early Warning of Critical Transitions in Biodiversity From Compositional Disorder." *Ecology* 97: 3079–3090. https://doi.org/10.1002/ecy.1558.

Ekblom, A., and L. Gillson. 2010a. "Dung Fungi as Indicators of Past Herbivore Abundance, Kruger and Limpopo National Park." *Palaeogeography, Palaeoclimatology, Palaeoecology* 296: 14–27.

Ekblom, A., and L. Gillson. 2010b. "Hierarchy and Scale: Testing the Long Term Role of Water, Grazing and Nitrogen in the Savanna Landscape of Limpopo National Park (Mozambique)." *Landscape Ecology* 25: 1529–1546.

Ellis, E. C. 2024. "The Anthropocene Condition: Evolving Through Social–Ecological Transformations." *Philosophical Transactions of the Royal Society B* 379, no. 1893: 20220255.

Ellis, E. C., and S. Wang. 1997. "Sustainable Traditional Agriculture in the Tai Lake Region of China." *Agriculture, Ecosystems and Environment* 61: 177–193.

Ernstson, H. 2014. "The Political Nature of Urban Wetlands: Speaking From Princess Vlei Wetland, Cape Town." 2, 1–3. http://www.situatedecologies.net.

Finlayson, C. M., S. J. Clarke, N. C. Davidson, and P. Gell. 2017. "Role of Palaeoecology in Describing the Ecological Character of Wetlands." *Marine and Freshwater Research* 67: 687–694.

Gell, P. 2024. "Ecological History of the Millewa (NSW) Wetlands: A Palaeoecological Study." Unpublished Report to NSW National Parks and Wildlife Service, Department of Climate Change, Energy, the Environment and Water.

Gell, P., K. Mills, and R. Grundell. 2012. "A Legacy of Climate and Catchment Change: The Real Challenge for Wetland Management." *Hydrobiologia* 708: 133–144.

Gell, P., and M. Reid. 2014. "Assessing Change in Floodplain Wetland Condition in the Murray Darling Basin, Australia." *Anthropocene* 8: 39–45.

Gell, P. A. 2019. "Watching the Tide Roll Away–Contested Interpretations of the Nature of the Lower Lakes of the Murray Darling Basin." *Pacific Conservation Biology* 26: 130–141.

Gell, P. A. 2020. "Restoring Murray River Floodplain Wetlands: Does the Sediment Record Inform on Watering Regime?" *River Research and Applications* 36: 620–629.

Gell, P. A., S. Bulpin, P. Wallbrink, G. Hancock, and S. Bickford. 2005. "Tareena Billabong–A Palaeolimnological History of an Ever-Changing Wetland, Chowilla Floodplain, Lower Murray–Darling Basin, Australia." *Marine and Freshwater Research* 56: 441–456.

Gell, P. A., M.-E. Perga, and C. M. Finlayson. 2018. "Changes Over Time." In *Freshwater Ecology and Conservation: A Handbook of Techniques*, edited by J. M. R. Hughes, 283–305. Oxford, UK: Oxford University Press.

Gell, P. A., and M. A. Reid. 2016. "Muddied Waters: The Case for Mitigating Sediment and Nutrient Flux to Optimize Restoration Response in the Murray-Darling Basin, Australia." *Frontiers in Ecology and Evolution* 4: 16.

Gibbard, P., M. Walker, A. Bauer, et al. 2022. "The Anthropocene as an Event, Not an Epoch." *Journal of Quaternary Science* 37, no. 3: 395–399.

Gillson, L., and K. I. Duffin. 2007. "Thresholds of Potential Concern as Benchmarks in the Management of African Savannahs." *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 362: 309–319.

Gillson, L., and A. Ekblom. 2009a. "Resilience and Thresholds in Savannas: Nitrogen and Fire as Drivers and Responders of Vegetation Transition." *Ecosystems* 12: 1189–1203.

Gillson, L., and A. Ekblom. 2009b. "Untangling Anthropogenic and Climatic Influence on Riverine Forest in the Kruger National Park, South Africa." *Vegetation History and Archaeobotany* 18: 171–185.

Gillson, L., and A. Ekblom. 2020. "Using Palaeoecology to Explore the Resilience of Southern African Savannas." *Koedoe* 62: 1–12.

Gillson, L., and R. Marchant. 2014. "From Myopia to Clarity: Sharpening the Focus of Ecosystem Management Through the Lens of Palaeoecology." *Trends in Ecology & Evolution* 29: 317–325.

Gordon, A., and H. Birks. 1972. "Numerical Methods in Quaternary Palaeoecology I. Zonation of Pollen Diagrams." *New Phytologist* 71: 961–979.

Grundell, R., P. Gell, K. Mills, and A. Zawadzki. 2012. "Interaction Between a River and Its Wetland: Evidence From the Murray River for Spatial Variability in Diatom and Radioisotope Records." *Journal of Paleolimnology* 47: 205–219.

Guiry, E. J., F. Beglane, P. Szpak, R. Schulting, F. McCormick, and M. P. Richards. 2018. "Anthropogenic Changes to the Holocene Nitrogen Cycle in Ireland. Science." *Advances* 4: eaas9383.

Guiry, E. J., M. Buckley, T. J. Orchard, et al. 2020. "Deforestation Caused Abrupt Shift in Great Lakes Nitrogen Cycle." *Limnology and Oceanography* 65: 1921–1935.

Guo, L. 2007. "Doing Battle With the Green Monster of Taihu Lake." *Science* 317: 1166.

Hannaford, M. J. 2018. "Long-Term Drivers of Vulnerability and Resilience to Drought in the Zambezi-Save Area of Southern Africa, 1505–1830." *Global and Planetary Change* 166: 94–106.

Hannaford, M. J. 2023. "Deep Histories of Food Systems in Eastern Africa and Current Patterns of Food Insecurity." *Nature Food* 4, no. 11: 949–960.

Harding, W. 1992. "A Contribution to the Knowledge of South African Coastal Vleis: The Limnology and Phytoplankton Periodicity of Princess Vlei, Cape Peninsula." *Water SA* 18: 121–130.

Harris, C., B. Oom, and R. Diamond. 1999. "A Preliminary Investigation of the Oxygen and Hydrogen Isotope Hydrology of the Greater Cape Town Area and an Assessment of the Potential for Using Stable Isotopes as Tracers." *Water SA* 25, no. 1: 15–24.

Harrison, A. D. 1962. "Hydrobiological Studies on Alkaline and Acid Still Waters in the Western Cape Province." *Transactions of the Royal Society of South Africa* 36, no. 4: 213–244. https://doi.org/10.1080/00359196209519050.

Hart, R. C. 1995. "South African Coastal Lakes." In *Wetlands of South Africa*, edited by G. I. Gowan, 103–130. Durban, South Africa: Department of Environmental Affairs and Tourism.

Häyhä, T., P. L. Lucas, D. P. van Vuuren, S. E. Cornell, and H. Hoff. 2016. "From Planetary Boundaries to National Fair Shares of the Global Safe Operating Space—How Can the Scales Be Bridged?" *Global Environmental Change* 40: 60–72.

Haynes, D., P. Gell, J. Tibby, G. Hancock, and P. Goonan. 2007. "Against the Tide: The Freshening of Naturally Saline Coastal Lakes, Southeastern South Australia." *Hydrobiologia* 591: 165–183.

Higgs, E., D. A. Falk, A. Guerrini, et al. 2014. "The Changing Role of History in Restoration Ecology." *Frontiers in Ecology and the Environment* 12: 499–506.

Higuera, P. E., S. Crausbay, B. N. Shuman, and K. D. Wolf. 2022. "Challenges to Forest Restoration in an Era of Unprecedented Climate and Wildfire Activity in Rocky Mountain Subalpine Forests." *Past Global Changes Magazine* 30, no. 1.

Hobbs, J. E., J. A. Lindesay, and H. A. Bridgman. 1998. *Climates of the Southern Continents: Present, Past and Future.* West Sussex, UK: John Wiley and Sons, Ltd.

Hoff, H., B. Nykvist, and M. Carson. 2014. ""Living Well, Within the Limits of Our Planet"?: Measuring Europe's Growing External Footprint." Stockholm Environment Institute.

Hughes, T. P., S. Carpenter, J. Rockström, M. Scheffer, and B. Walker. 2013. "Multiscale Regime Shifts and Planetary Boundaries." *Trends in Ecology & Evolution* 28: 389–395.

Humphries, P. 2007. "Historical Indigenous Use of Aquatic Resources in Australia's Murray-Darling Basin, and Its Implications for River Management." *Ecological Management and Restoration* 8, no. 2: 106–113.

Illenberger, W. K. 1996. "The Geomorphologic Evolution of the Wilderness Dune Cordons, South Africa." *Quaternary International* 33: 11–20. https://doi.org/10.1016/1040-6182(95)00099-2.

IPCC. 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. Masson-Delmotte, P. Zhai, A. Pirani, et al. Cambridge, UK: Cambridge University Press.

Jackson, S., and L. Head. 2020. "Australia's Mass Fish Kills as a Crisis of Modern Water: Understanding Hydrosocial Change in the Murray-Darling Basin." *Geoforum* 109: 44–56.

Jacobson, M. J. 2022. "Archaeological Evidence for Community Resilience and Sustainability: A Bibliometric and Quantitative Review." *Sustainability* 14, no. 24: 16591.

Jensen, A. 2002. "Repairing Wetlands of the Lower Murray: Learning From Restoration Practice." *Ecological Management and Restoration* 3: 5–14.

Kariuki, R. W., L. K. Munishi, C. J. Courtney-Mustaphi, et al. 2021. "Integrating Stakeholders' Perspectives and Spatial Modelling to Develop Scenarios of Future Land Use and Land Cover Change in Northern Tanzania." *PLoS One* 16, no. 2: e0245516.

Kattel, G., X. Dong, and X. Yang. 2014. "Cladoceran-Inferred Ecological and Hydrological Changes of Two Floodplain Wetlands in Two Large River Systems, the Murray (Australia) and Yangtze Rivers (China)." In *Australia-China Wetland Network Research Partnership*, edited by G. Kattel. Mt. Helen, Australia: Collaborative Research Network, Federation University Australia.

Keane, R. E., P. F. Hessburg, P. B. Landres, and F. J. Swanson. 2009. "The Use of Historical Range and Variability (HRV) in Landscape Management." *Forest Ecology and Management* 258: 1025–1037.

Kirsten, K. L., T. Haberzettl, M. Wündsch, et al. 2018. "A Multiproxy Study of the Ocean-Atmospheric Forcing and the Impact of Sea-Level Changes on the Southern Cape Coast, South Africa During the Holocene." *Palaeogeography, Palaeoclimatology, Palaeoecology* 496, no. January: 282–291. https://doi.org/10.1016/j.palaeo.2018.01.045.

Kirsten, K. L., and M. E. Meadows. 2016. "Late-Holocene Palaeolimnological and Climate Dynamics at Princessvlei, South Africa: Evidence From Diatoms." *Holocene* 26, no. 9: 1371–1381. https://doi.org/10.1177/0959683616640049.

Lin, Q., K. Zhang, S. McGowan, E. Capo, and J. Shen. 2021. "Synergistic Impacts of Nutrient Enrichment and Climate Change on Long-Term Water Quality and Ecological Dynamics in Contrasting Shallow-Lake Zones." *Limnology and Oceanography* 66: 3271–3286. https://doi.org/10.1002/lno.11878.

Lin, Q., K. Zhang, S. McGowan, et al. 2023. "Characterization of Lacustrine Harmful Algal Blooms Using Multiple Biomarkers: Historical Processes, Driving Synergy, and Ecological Shifts." *Water Research* 235: 119916.

Lin, Q., K. Zhang, J. Shen, and E. Liu. 2019. "Integrating Long-Term Dynamics of Ecosystem Services Into Restoration and Management of Large Shallow Lakes." *Science of the Total Environment* 671: 66–75.

Lunstrum, E. 2015. "Conservation Meets Militarisation in Kruger National Park: Historical Encounters and Complex Legacies." *Conservation and Society* 13, no. 4: 356–369.

Lyman, R. L. 2006. "Paleozoology in the Service of Conservation Biology." *Evolutionary Anthropology: Issues, News, and Reviews* 15: 11–19.

Lyman, R. L. 2012. "A Warrant for Applied Palaeozoology." *Biological Reviews* 87: 513–525.

Macumber, P. G. 1991. "Interaction Between Groundwater and Surface Systems in Northern Victoria." Department of Conservation and Environment.

Marais, K. 2019. "Freshwater Ecological Assessment as Part of the Environmental Authorisation and Water Use Licence Application for the Proposed Princess Vlei Circulatory Trail in Grassy Park, Western Cape Province."

Marchant, R., S. Richer, O. Boles, et al. 2018. "Drivers and Trajectories of Land Cover Change in East Africa: Human and Environmental Interactions From 6000 Years Ago to Present." *Earth-Science Reviews* 178: 322–378.

Martin, A. 1956. "The Ecology and History of Groenvlei." *South African Journal of Science* 52: 187–192.

Martin, A. 1962. "Evidence Relating to the Quaternary History of the Wilderness Lakes." *South African Journal of Geology* 65: 19–42.

Masson-Delmotte, V., P. Zhai, A. Pirani, et al. 2021. "Climate Change 2021: The Physical Science Basis." Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change 2.

Mayfield, R. J., J. A. Dearing, C. P. Doncaster, and P. G. Langdon. 2022. "Stability of Chironomid Community Structure During Historic Climatic and Environmental Change in Subarctic Alaska." *Limnology and Oceanography* 67: S444–S460.

Mayfield, R. J., P. G. Langdon, C. P. Doncaster, et al. 2020. "Metrics of Structural Change as Indicators of Chironomid Community Stability in High Latitude Lakes." *Quaternary Science Reviews* 249: 106594. https://doi.org/10.1016/j.quascirev.2020.106594.

Mayfield, R. J., P. G. Langdon, C. P. Doncaster, et al. 2021. "Late Quaternary Chironomid Community Structure Shaped by Rate and Magnitude of Climate Change." *Journal of Quaternary Science* 36: 360–376.

McLaughlin, J. F. 2018. "Safe Operating Space for Humanity at a Regional Scale." *Ecology and Society* 23, no. 2: 43.

Meadows, M. E. 2014. "Recent Methodological Advances in Quaternary Palaeoecological Proxies." *Progress in Physical Geography* 38, no. 6: 807–817.

Meskell, L. 2009. "The Nature of Culture in Kruger National Park." In *Cosmopolitan Archaeologies*, edited by L. Meskell, 89–112. Durham, NC: Duke University Press.

Millar, C. I. 2014. "Historic Variability: Informing Restoration Strategies, Not Prescribing Targets." *Journal of Sustainable Forestry* 33: S28–S42.

Millhauser, J. K., and T. K. Earle. 2022. "Biodiversity and the Human Past: Lessons for Conservation Biology." *Biological Conservation* 272: 109599.

Morgan, P., G. H. Aplet, J. B. Haufler, H. C. Humphries, M. M. Moore, and W. D. Wilson. 1994. "Historical Range of Variability: A Useful Tool for Evaluating Ecosystem Change." *Journal of Sustainable Forestry* 2, no. 1–2: 87–111. https://doi.org/10.1300/J091v02n01_04.

Morrison, K. D., E. Hammer, O. Boles, et al. 2021. "Mapping Past Human Land Use Using Archaeological Data: A New Classification for Global Land Use Synthesis and Data Harmonization." *PLoS One* 16: e0246662.

Mottl, O., S. G. Flantua, K. P. Bhatta, et al. 2021. "Global Acceleration in Rates of Vegetation Change Over the Past 18,000 Years." *Science* 372: 860–864.

Mottl, O., J.-A. Grytes, A. W. Seddon, et al. 2021. "Rate-Of-Change Analysis in Palaeoecology Revisited: A New Approach." *Review of Palaeobotany and Palynology* 293: 104483.

Neumann, F. H., L. Scott, and M. K. Bamford. 2011. "Climate Change and Human Disturbance of Fynbos Vegetation During the Late Holocene at Princess Vlei, Western Cape, South Africa." *Holocene* 21, no. 7: 1137–1149. https://doi.org/10.1177/0959683611400461.

Newall, P. R., L. N. Lloyd, P. A. Gell, and K. F. Walker. 2015. "Implications of Environmental Trajectories for Limits of Acceptable Change: A Case Study of the Riverland Ramsar Site, South Australia." *Marine and Freshwater Research* 67: 738–747.

Norris, R. H., P. Liston, N. Davies, et al. 2001. "Snapshot of the Murray-Darling Basin River Condition." Murray–Darling Basin Commission, Canberra.

North, M. P., and W. S. Keeton. 2008. "Emulating Natural Disturbance Regimes: An Emerging Approach for Sustainable Forest Management." In *Patterns and Processes in Forest Landscapes*, 341–372. Dordrecht, the Netherlands: Springer Netherlands.

Nykvist, B., Å. Persson, and L. Persson. 2013. "National Environmental Performance on Planetary Boundaries." https://coilink.org/20.500.12592/0gs605 on 26 Nov 2024. COI: 20.500.12592/0gs605.

Olds, A. A., N. C. James, M. K. S. Smith, and O. L. F. Weyl. 2016. "Fish Communities of the Wilderness Lakes System in the Southern Cape, South Africa." *Koedoe* 58, no. 1: a1364. https://doi.org/10.4102/koedoe.v58i1.1364.

Oliver, I., J. Dorrough, and S. K. Travers. 2023. "The Acceptable Range of Variation Within the Desirable Stable State as a Measure of Restoration Success." *Restoration Ecology* 31: e13800.

Orton, J., G. Avery, D. Halkett, T. Hart, and J. Kaplan. 2020. "Precolonial Coastal Archaeology Between Table Bay and Yzerfontein, Western Cape, South Africa: A Review of Historical and Recent Observations." *Southern African Humanities* 33, no. 1: 133–168.

Petek-Sargeant, N., and P. J. Lane. 2021. "Weathering Climate Change in Archaeology: Conceptual Challenges and an East African Case Study." *Cambridge Archaeological Journal* 31, no. 3: 437–454.

Pittock, J., S. Corbett, M. J. Colloff, et al. 2023. "A Review of the Risks to Shared Water Resources in the Murray–Darling Basin." *Australasian Journal of Water Resources* 27, no. 1: 1–17.

Pritchard, D. 2021. "The 'Ecological Character' of Wetlands: A Foundational Concept in the Ramsar Convention, Yet Still Cause for Debate 50 Years Later." *Marine and Freshwater Research* 73: 1127–1133.

Qin, B., H. W. Paerl, J. D. Brookes, et al. 2019. "Why Lake Taihu Continues to Be Plagued With Cyanobacterial Blooms Through 10 Years (2007–2017) Efforts." *Science Bulletin* 64: 354–356.

Quick, L. J., B. M. Chase, M. Wündsch, et al. 2018. "A High-Resolution Record of Holocene Climate and Vegetation Dynamics From the Southern Cape Coast of South Africa: Pollen and Microcharcoal Evidence From Eilandvlei." *Journal of Quaternary Science* 33, no. 5: 487–500. https://doi.org/10.1002/jqs.3028.

Randall, R. 1995. "Ramsar: Wilderness Lakes, South Africa." List of Wetlands of International Importance. https://rsis.ramsar.org/ris/524.

Raworth, K. 2012. "A Safe and Just Space for Humanity: Can We Live Within the Doughnut?" Oxfam.

Reid, M. A., C. D. Sayer, A. P. Kershaw, and H. Heijnis. 2007. "Palaeolimnological Evidence for Submerged Plant Loss in a Floodplain Lake Associated With Accelerated Catchment Soil Erosion (Murray River, Australia)." *Journal of Paleolimnology* 38: 191–208.

Richardson, K., W. Steffen, W. Lucht, et al. 2023. "Earth Beyond Six of Nine Planetary Boundaries." *Science Advances* 9: eadh2458.

Rivera-Collazo, I. 2022. "Environment, Climate and People: Exploring Human Responses to Climate Change." *Journal of Anthropological Archaeology* 68: 101460.

Roberts, D. L., M. D. Bateman, C. V. Murray-Wallace, A. S. Carr, and P. J. Holmes. 2009. "West Coast Dune Plumes: Climate Driven Contrasts in Dunefield Morphogenesis Along the Western and Southern South African Coasts." *Palaeogeography, Palaeoclimatology, Palaeoecology* 271, no. 1–2: 24–38. https://doi.org/10.1016/j.palaeo.2008.09.009.

Roberts, P., C. Hunt, M. Arroyo-Kalin, D. Evans, and N. Boivin. 2017. "The Deep Human Prehistory of Global Tropical Forests and Its Relevance for Modern Conservation." *Nature Plants* 3, no. 8: 1–9.

Rockström, J., J. Gupta, D. Qin, et al. 2023. "Safe and Just Earth System Boundaries." *Nature* 619: 102–111.

Rockström, J., W. Steffen, K. Noone, et al. 2009b. "A Safe Operating Space for Humanity." *Nature* 461: 472–475.

Rockström, J., W. Steffen, K. Noone, et al. 2009a. "Planetary Boundaries: Exploring the Safe Operating Space for Humanity." *Ecology and Society* 14, no. 2: 32.

Rodionov, S. N. 2004. "A Sequential Algorithm for Testing Climate Regime Shifts." *Geophysical Research Letters* 31, no. 9: L09204.

Rodionov, S. N. 2006. "Use of Prewhitening in Climate Regime Shift Detection." *Geophysical Research Letters* 33, no. 12: L12707.

Russell, I. 1999. "Changes in the Water Quality of the Wilderness and Swartvlei Lake Systems, South Africa." *Koedoe* 42, no. 1: 57–72.

Russell, I. 2013. "Spatio-Temporal Variability of Surface Water Quality Parameters in a South African Estuarine Lake System." *African Journal of Aquatic Science* 38, no. 1: 53–66. https://doi.org/10.2989/16085914.2012.742006.

Russell, I., R. Randall, N. Cole, T. Kraaij, and N. Kruger. 2012. "Garden Route National Park Wilderness Coastal Area – State of Knowledge." Wilderness.

Scheffer, M., S. R. Carpenter, T. M. Lenton, et al. 2012. "Anticipating Critical Transitions." *Science* 338: 344–348. https://doi.org/10.1126/science.1225244.

Scientific Aquatic Services. 2020. "Freshwater Ecological Assessment as Part of the Environmental Authorisation and Water Use Licence Application for the Proposed Princess Vlei Circulatory Trail in Grassy Park, Western Cape Province." www.sasenvironmental.co.za.

Seddon, A. W., C. A. Froyd, A. Witkowski, and K. J. Willis. 2014. "A Quantitative Framework for Analysis of Regime Shifts in a Galápagos Coastal Lagoon." *Ecology* 95: 3046–3055.

Seddon, A. W., M. Macias-Fauria, and K. J. Willis. 2015. "Climate and Abrupt Vegetation Change in Northern Europe Since the Last Deglaciation." *Holocene* 25: 25–36.

Simpson, G. L. 2018. "Modelling Palaeoecological Time Series Using Generalised Additive Models." *Frontiers in Ecology and Evolution* 6: 149.

Steffen, W., W. Broadgate, L. Deutsch, O. Gaffney, and C. Ludwig. 2015. "The Trajectory of the Anthropocene: The Great Acceleration." *Anthropocene Review* 2: 81–98.

Steffen, W., K. Richardson, J. Rockström, et al. 2015. "Planetary Boundaries: Guiding Human Development on a Changing Planet." *Science* 347, no. 6223: 1259855. https://doi.org/10.1126/science.1259855.

Steffen, W., J. Rockström, K. Richardson, et al. 2018. "Trajectories of the Earth System in the Anthropocene." *Proceedings of the National Academy of Sciences* 115, no. 33: 8252–8259.

Su, Y., X. Dong, Y. Li, Q. Hong, and R. Flower. 2023. "Optimizing Safe and Just Operating Spaces at Sub-Watershed Scales to Guide Local Environmental Management." *Journal of Cleaner Production* 398: 136530.

Thomas, C. D., J. K. Hill, C. Ward, and J. H. Hatfield. 2022. "FAR-Sighted Conservation." *Ecological Solutions and Evidence* 3, no. 4: e12188.

Thompson, J. R., S. L. Duncan, and K. N. Johnson. 2008. "Is There Potential for the Historical Range of Variability to Guide Conservation Given the Social Range of Variability?" *Ecology and Society* 14, no. 1: 18. http://www.ecologyandsociety.org/vol14/iss1/art18/.

Turner, R. A., and J. Wills. 2022. "Downscaling Doughnut Economics for Sustainability Governance." *Current Opinion in Environmental Sustainability* 56: 101180.

Underhill, L. 2017. "An Analysis of the Ability of Small Urban Wetlands to Treat Stormwater: The Case of Princess Vlei Wetland, Cape Town [Masters Degree]." University of Cape Town.

Underhill, L. 2018. "An Analysis of the Ability of Small Urban Wetlands to Treat Stormwater: The Case of Princess Vlei Wetland, Cape Town." University of Cape Town.

van Leeuwen, J. F., C. A. Froyd, W. Van der Knaap, E. E. Coffey, A. Tye, and K. J. Willis. 2008. "Fossil Pollen as a Guide to Conservation in the Galápagos." *Science* 322: 1206.

van Leeuwen, J. F. N., H. Schäfer, W. O. van der Knapp, T. Rittenour, S. Björck, and B. Ammann. 2005. "Native or Introduced? Fossil Pollen and Spores May Say. An Example From the Azores Islands." *Neobiota* 6: 27–34.

Veblen, T. T. 2003. "Historic Range of Variability of Mountain Forest Ecosystems: Concepts and Applications." *Forestry Chronicle* 79: 223–226.

Verhoef, J. 1986. "Notes on Archaeology and Prehistoric Mining in the Kruger National Park." *Koedoe* 29, no. 1: 149–156.

Wang, R., J. A. Dearing, C. P. Doncaster, et al. 2019. "Network Parameters Quantify Loss of Community Structure in Human-Impacted Lake Ecosystems." *Global Change Biology* 25: 3871–3882. https://doi.org/10.1111/gcb.14776.

Wang, R., J. A. Dearing, and P. G. Langdon. 2022. "Critical Transitions in Lake Ecosystem State May be Driven by Coupled Feedback Mechanisms: A Case Study From Lake Erhai, China." *Water* 14: 85.

Wang, R., J. A. Dearing, P. G. Langdon, et al. 2012. "Flickering Gives Early Warning Signals of a Critical Transition to a Eutrophic Lake State." *Nature* 492: 419–422. https://doi.org/10.1038/nature11655.

Wündsch, M., T. Haberzettl, H. C. Cawthra, et al. 2018. "Holocene Environmental Change Along the Southern Cape Coast of South Africa – Insights From the Eilandvlei Sediment Record Spanning the Last 8.9 Kyr." *Global and Planetary Change* 163: 51–66. https://doi.org/10.1016/j.gloplacha.2018.02.002.

Xu, D., Y. Cai, X. Wu, H. Jiang, X. Leng, and S. An. 2015. "Regime Shifts and Resilience of the Lake Taihu Social-Ecological System Under Long-Term External Disturbance (1960s–2000s)." *CLEAN – Soil, Air, Water* 43: 561–568.

Xu, X., G. Yang, Y. Tan, et al. 2017. "Impacts of Land Use Changes on Net Ecosystem Production in the Taihu Lake Basin of China From 1985 to 2010." *Journal of Geophysical Research: Biogeosciences* 122: 690–707.

Xu, X., G. Yang, Y. Tan, et al. 2016. "Ecological Risk Assessment of Ecosystem Services in the Taihu Lake Basin of China From 1985 to 2020." *Science of the Total Environment* 554: 7–16.

Zhang, Y., S. Li, F. Wei, and Z. Liang. 2023. "A Method of Evaluating Safe Operating Space: Focus on Geographic Regions, Income Levels and Developing Pathway." *Environmental Management* 71: 821–834.

Zhang, Y., X. Liu, B. Qin, K. Shi, J. Deng, and Y. Zhou. 2016. "Aquatic Vegetation in Response to Increased Eutrophication and Degraded Light Climate in Eastern Lake Taihu: Implications for Lake Ecological Restoration." *Scientific Reports* 6: 23867.