Geoheritage (2022) 14:126
https://doi.org/10.1007/s12371-022-00753-1

ORIGINAL ARTICLE

Planning for Climate Change Impacts on Geoheritage Interests in Protected and Conserved Areas

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Received: 23 June 2022 / Accepted: 31 October 2022
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Abstract
Climate change presents challenges for the management of geoheritage at all scales from individual geosites to whole landscapes, and affecting all areas of the planet. Direct impacts will arise principally through the effects of climate changes on geomorphological processes and vegetation cover, while indirect impacts will result from hard engineering interventions to mitigate risks from natural hazards. We present an indicative framework that sets out key steps to help geoconservation practitioners and managers of all protected and conserved areas (PCAs) with geoheritage interests to assess and manage the impacts of climate change on geoheritage. Strategies for mitigation and adaptation to assist contingency planning and implementation should be supported by site condition monitoring and as far as possible work with nature, but will require to be adaptive in the face of many uncertainties. Our approach is based on assessment of the risk of degradation of geosites and their features and processes arising from the likelihood of climate change affecting them and the predicted severity of impacts. The risk of degradation of a site, feature or process will depend on (i) its geographic location and proximity to geomorphological systems that are likely to respond dynamically to climate changes; (ii) the magnitude, rate and duration of these changes; and (iii) intrinsic factors that include the geological and physical characteristics of the site and its features and processes. Management options range from non-intervention to planned interventions informed by the risk of degradation assessment. However, documentation for posterity may be the only practical option for geoheritage interests close to existential thresholds, such as small mountain glaciers, and sites at risk from sea-level rise and coastal or river erosion. Adaptation strategies for geoheritage in protected and conserved areas should, as far as practicable, align with those for biodiversity and aim to deliver multiple co-benefits for nature and people, although economic, social and political constraints may hinder implementation where wider stakeholder interests are involved. Managers of PCAs will need substantial input from geoconservation experts to carry out the assessments recommended and determine the action required.

Keywords Geoheritage · Geoconservation · Climate change impacts · Risk of degradation · Adaptation planning · Nature-based solutions

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Published online: 19 November 2022

Introduction

Climate change is a natural phenomenon, well documented over different timescales in geological records (Westerhold et al. 2020; Lear et al. 2021; Rae et al. 2021), but is now being significantly amplified by anthropogenic release of greenhouse gases and consequent feedbacks (IPCC 2021). This amplified climate change is an additional source of stress on geoheritage sites, or geosites, and their features and processes of interest, compounding the effects of other pressures, such as urban, commercial, industrial and infrastructure developments, mineral extraction, changes in land use, coastal protection, and river engineering for flood defences. The IUCN World Heritage Outlook 3 identified climate change as the most common threat to natural World Heritage sites listed under criterion viii (geology) (Osipova et al. 2020). Climate change will directly affect different types and locations of geoheritage interests in different ways; for example, most inland rock exposures will be relatively robust, but coastal features may be lost through accelerated erosion or become inaccessible under rising sea levels, while geomorphological process systems such as those of coastal, desert or mountain environments may become more dynamic and their responses have wider ecosystem and landscape impacts. In addition, there will be increased hazards to geosite visitors and impacts on geotourism and the wider range of ecosystem services provided by geoheritage and geodiversity. Indirectly, access to sites will be prevented and geomorphological processes disrupted where hard coast defences and flood protection measures are installed to protect property and infrastructure. Climate action plans for protected and conserved areas (PCAs), the main mechanism for geoconservation, will need to take these aspects into account and to consider adaptation and mitigation measures for geoheritage in conjunction with those for biodiversity and cultural heritage where multiple conservation interests are present.

Changes in the physical environment arising from climate change, notably in geomorphological processes, are well documented (IPCC 2019), but the potential risk of degradation of geosites and their interests and the management challenges it presents have received comparatively little attention. However, the wider role of geoscience in understanding and adapting to climate change has been strongly emphasised (Burn et al. 2021; Lear et al. 2021). Building on existing groundwork (Prosser et al. 2010; Sharples 2011; Brown et al. 2012; García-Ortiz et al. 2014; Wignall et al. 2018), this paper outlines the potential impacts of climate change on geoheritage, presents an indicative framework to assist geoconservation practitioners, conservation managers and others to assess the risk of degradation of geosites and their interests, and sets out a portfolio of adaptation strategies. It also situates geoheritage adaptation in the context of the wider transition towards future-proofing nature conservation in the face of climate change (van Kerkhoff et al. 2019). Possible management and adaptation options follow the IUCN *Guidelines for Geoconservation in Protected and Conserved Areas* (Crofts et al. 2020) and apply to geoheritage interests in all categories of PCAs, and those included under other effective area-based conservation measures (OECMs) (Dudley 2008; IUCN-WCPA Task Force on OECMs 2019) and in geoparks. Among the key recommendations are the need for a flexible approach informed by regional rather than global climate models, monitoring of changes that will be unpredictable in scale and effect, and as far as possible to adopt nature-based solutions rather than attempt to 'fix and control' natural processes through heavily engineered interventions.

Implications of Climate Change

According to IPCC projections (IPCC 2021), global mean temperatures will continue to increase over the twenty-first century. For example, under an intermediate greenhouse gas emissions scenario (SSP2-4.5, with emissions remaining around current levels until the middle of the century), global mean surface temperature by the end of the present century is very likely to be 2.1 to 3.5 °C higher compared with the average for 1850–1900. On a geological timescale, global surface temperature was last sustained at such a level ~ 3 million years ago. Global precipitation will increase, with a likelihood of more intense rainfall. Abiotic environmental changes will be magnified as glaciers recede and permafrost thaws, deserts expand, the magnitude and frequency of soil erosion, coastal erosion, rockfalls, flooding and wildfires increase, and river flow and sediment transfer regimes adjust. As well as gradual changes, including changes in seasonality and interannual variability, increased frequency and intensity of extreme geomorphological events such as droughts, floods, landslides and changes in landscape disturbance regimes may be expected, with less recovery time between events. However, since such changes and their effects will be highly variable across the Earth, global projections from general circulation models (GCMs) need to be downscaled through national and regional scales. The Intergovernmental Panel on Climate Change (IPCC) and the Coordinated Regional Climate Downscaling Experiment (CORDEX) have prepared regional projections and downscaled models (Copernicus 2021; IPCC 2021; CORDEX 2022), and many national and regional governments have developed more specific downscaled models—for example, through the UK Climate Projections (https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index), and the State of California, USA (https://www.energy.ca.gov/sites/default/files/2019-11/Statewide_Reports-SUM-CCCA4-2018-013_State wide_Summary_Report_ADA.pdf). These downscaled models enable the assessment of likely impacts on PCAs based on more local conditions than the global models.

At the coast, sea level will continue to rise as a consequence of ice sheet melting and ocean expansion in a warmer world. For example, by 2100, under the intermediate greenhouse gas emissions scenario, global mean sea level is likely to rise by 0.44–0.76 m relative to 1995–2014, but could approach 2 m under a very high emissions scenario (IPCC 2021). However, rates will vary geographically according to gravitational effects, ocean circulation factors and variations in vertical land movements arising from glacio-isostatic adjustments and tectonic factors, with effects exacerbated regionally by increased frequency of extreme sea levels arising from a combination of storm surges, waves and tides (Tebaldi et al. 2021; Calafat et al. 2022). Use of regional rather than global estimates is therefore recommended for management planning of responses in PCAs in order to reduce the uncertainty in scale and timing of effects in local areas.

Addressing Climate Change Impacts on Geoheritage in PCAs: an Indicative Planning Framework

To assist PCA managers and others to address the geoconservation challenges arising from climate change, we outline an indicative planning framework comprising a number of procedural steps (Table 1). Broadly following the IUCN adaptation cycle (Gross et al. 2016) and the adaptation frameworks of Parks Canada (Nelson et al. 2020) and the USA National Park Service (National Park Service 2021), the framework is intended to enable understanding of how changes in climate conditions may impact the values and management requirements of geoheritage interests. We then present adaptation options and actions to enable PCA managers to factor geoheritage interests into their decision-making processes and climate change action plans alongside other considerations. The framework and the responses outlined can be adapted to local circumstances, with adjustments made for differences in the type and rate of climate changes and the site-specific management actions required. Key elements of the framework have been applied and tested successfully in Scotland, including a qualitative assessment of risk of degradation based on expert judgement (Wignall et al. 2018; Wignall 2019).

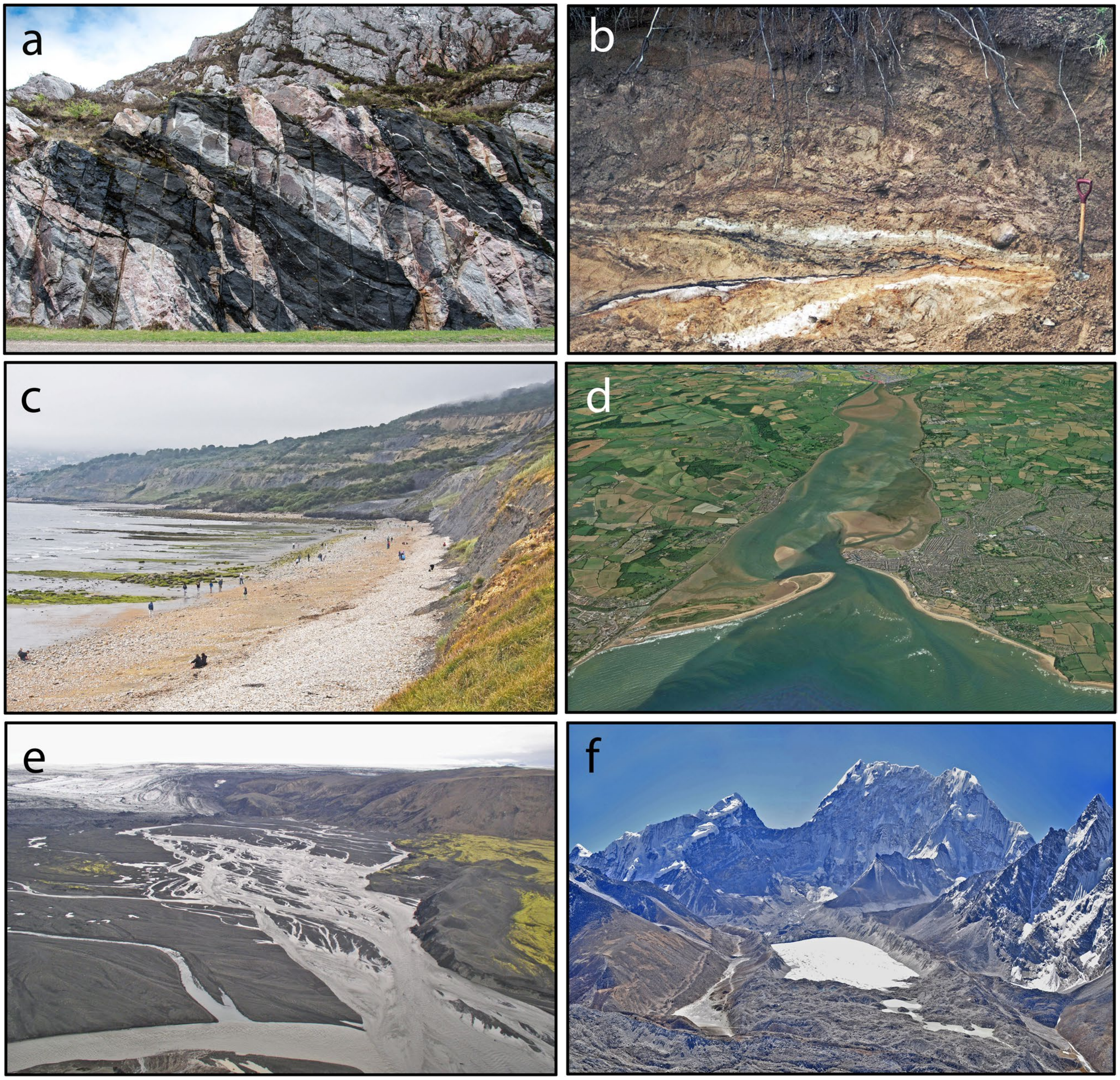
We use the term 'geosite' to refer to any site that has a single or multiple geological or geomorphological features and/or processes worthy of protection principally on account of their scientific value, although they may also have supporting educational, cultural, aesthetic and ecological values (Crofts et al. 2020). A PCA may comprise a single geosite or multiple geosites where geoheritage is the primary conservation interest, or the geoheritage may form part of a broader range of biodiversity or cultural interests within a PCA.

Evaluation of Climate Impacts and Risk Assessment

Step 1: Identify Geosites and Their Features and Processes of Interest The first step is to determine the locations and values of geosites within a PCA and the features and processes

Table 1 Indicative framework and key steps in assessing and adapting to the impacts of climate change on geoheritage in PCAs

	Steps	Actions
Evaluation of climate impacts and risk assessment	1	Undertake a geoheritage inventory to identify geosites and their features and processes of interest, and their values, types and locations
	2	For each feature present and the processes operating in a geosite, define the conservation objectives (taking into account climate change) and a condition, or range of conditions, considered to encompass its desirable conservation state or 'favourable condition'
	3	Identify climate change drivers (e.g. increased rainfall, rising sea level) that may affect a geosite and all likely direct and indirect impacts from these on the site and its features and processes, using projections from downscaled climate models under different greenhouse gas emissions scenarios, and evaluate potential societal drivers (e.g. demands for hard flood defences) that may also result in impacts
	4	Determine the risk of degradation from favourable condition state, for the site and its features and processes of interest, resulting from each identified climate change impact drivers
Adaptation planning and implementation	5	Assess current management with respect to the climate change drivers, identify and assess adaptation options, and undertake contingency planning for implementation of these options, including liaison and partnership working with other stakeholders where appropriate
	6	Identify key indicators and triggers to activate management action and undertake site condition monitoring at appropriate time intervals
	7	Implement management intervention if decision thresholds are triggered
	8	Monitor, evaluate, review and learn. Adapt conservation objectives as necessary and repeat key steps above



that require conservation. PCAs may range in scale from small geosites and geological monuments to extensive protected areas with multiple geosites and geoheritage interests. In the former case, a simple site survey should suffice. If the management unit is a large and complex PCA, such as a national park, then a full inventory and evaluation of geosites, and their component features and processes of interest, is essential (Crofts et al. 2020). To assess risk from climate change, each geosite feature and process should be categorised according to factors that help determine this risk. Site type (e.g. active or relict, finite or extensive) and location (e.g. quarry, river reach or foreshore) are fundamental to identifying many likely pressures (Prosser et al. 2018; Wignall et al. 2018; Crofts et al. 2020) (Fig. 1). However, the dependence of a feature or process on the water environment, such as whether fluvial and coastal processes form and alter it, it is exposed by river or wave action, or requires to be water saturated (such as bog-preserved pollen records), is also crucial for identifying climate change risk (Wignall et al. 2018).

Step 2: Define Conservation Objectives and Baseline Favourable Condition The second step is to define conservation objectives (taking into account climate change) and a condition, or range of conditions, for each geosite feature or process, that is considered to encompass its desirable

◂**Fig. 1** Examples of geoheritage features and processes in different categories of PCA and their susceptibilities to climate change. Management options will depend on assessment of the risk of degradation and the particular site circumstances and characteristics (see text for discussion). **a** Roadside exposure in Precambrian Lewisian gneiss, North West Highlands UNESCO Global Geopark, Scotland. Hard rock exposures in road cuttings and disused quarries are likely to be relatively robust in the face of climate change, but may require intermittent clearance of vegetation to maintain visibility of key features (photo: John Gordon). **b** Pleistocene interglacial podzol in a disused quarry, Teindland Quarry Site of Special Scientific Interest, Scotland. Exposures in Pleistocene sediments are susceptible to accelerated weathering and loss of visibility through vegetation encroachment and accumulation of talus. Intermittent vegetation clearance and re-excavation may be necessary to maintain exposures for scientific study, but may result in loss of the interest if it is limited in extent (photo: John Gordon). **c** Dorset coast, part of the Jurassic Coast World Heritage site, England. Coastal cliff exposures are susceptible to increased frequency and magnitude of rockfalls and landslides, increased marine erosion and vegetation encroachment. Foreshore exposures are susceptible to loss of access through rising sea levels, burial by landslides from adjacent cliffs or enhanced sediment transfer by longshore drift. Recording and/or rescue (removal for ex situ preservation) may be the only viable geoconservation options in such situations (photo: John Gordon). **d** Exe estuary, Devon, England, is a Ramsar site, Special Protection Area and a Site of Special Scientific Interest. It includes the nationally important sand spit of Dawlish Warren (centre). Active coastal systems are likely to move landwards under rising sea level, but where hard barriers (e.g. roads, railways and built-up areas) impede this movement, beaches, dunes and saltmarshes may re-locate or disappear. In estuaries, large-scale coastal reorganisation may occur as patterns of erosion and sedimentation are altered. Preferred management options are to allow the systems to evolve without intervention but this may be complicated if property, infrastructure or recreational space exist within the wider coastal system and require hard coast defences where there is inadequate space to deploy nature-based solutions. (Image: Google Earth™). **e** Braided meltwater rivers, Tungnaárjökull, Vatnajökull National Park, Iceland. River systems may become more dynamic with changes in the magnitude and frequency of flooding from increased precipitation or glacier melting, seasonal discharge and sediment transfer. Preferred management options are to allow rivers to evolve without intervention and to maintain geomorphological connectivity within their whole catchments, including with the adjacent floodplains. It may be necessary to extend PCA boundaries to accommodate channel changes or to develop nature-based solutions as a first course of action, if feasible, but in places the only recourse might be hard engineering solutions where property, infrastructure or agricultural land require protection (photo: John Gordon). **f** Imja Tsho, Sagarmatha National Park, Nepal. Shrinking glaciers represent a loss of geoheritage and landscape aesthetic value, reduce dry-season water availability downstream and increase glacial lake outburst flood hazard downstream, but produce new proglacial landform assemblages. Management options may require essential hazard mitigation activities, such as artificially lowering lake levels. (Photo: Sharad Joshi, CC BY-SA 3.0) (Creative Commons Attribution-Share Alike 3.0 Unported license)

conservation state or 'favourable condition' (e.g. that key rock units in an exposure should remain visible and accessible, or that a particular assemblage of landforms and geomorphological processes should continue to exist unimpeded by artificial barriers). Once this 'baseline' is defined, any climate change drivers that put, or are projected to put, the geosite outside of its acceptable condition will trigger management intervention. Also, sites may be at risk from changes outside the conservation area boundary (e.g. through upstream changes affecting river discharge and sediment throughput downstream).

Geosites will primarily be of high geoscientific value, but additional educational, aesthetic, cultural, spiritual and ecological values should be factored into management responses to climate change where relevant. For example, many sites have remarkable natural features or aesthetic qualities and are valued for geotourism, while others support special habitats and species (Crofts et al. 2020).

Step 3: Identify Potential Impacts of Climate Change The third step is to identify the potential stresses and impacts on geosites and their features and processes from climate change, recognising that these may compound other pressures additively or synergistically. These potential stressors, such as changes in temperature, precipitation, stream discharge, sea level and wind velocity, drive impacts to geoheritage (e.g. Coats 2010). Identifying the drivers of climate change impacts helps to better define the nature of the threat and the management actions that can be taken to mitigate or adapt to the impact drivers. The effects of drivers such as gradual degradation, changes in the frequency and severity of extreme events (e.g. flooding) and seasonal changes should all be considered. The stresses and impacts may be direct or indirect.

Direct impacts will arise principally through climate-driven changes in geomorphological processes in the hydrosphere and cryosphere, and in vegetation cover (Table 2). A comprehensive review of the physical changes and impacts summarised in Table 2 is outside the scope of this paper, and many of these are described elsewhere (IPCC 2019, 2021, 2022). Briefly, active process interests may become more or less dynamic, processes may change entirely or cease to operate, while new landscapes may emerge (e.g. in proglacial areas as glaciers retreat and disappear; Reynard 2021; Zimmer et al. 2021). Some geomorphological systems may become more dynamic as the magnitude and frequency of storms and rainfall events increase, resulting in enhanced soil erosion, debris flows, landslides and transfer of sediment into rivers, whereas others may become moribund under warmer or drier climates (e.g. reduction of periglacial process activity on lower mountains). The former may produce greater geodiversity (with concomitant environmental heterogeneity benefits for biodiversity); the latter, reduced geodiversity. There may be changes in geomorphological process rates, frequency and intensity, including less recovery time between extreme events, changes in dominant processes and spatial changes in the locations of processes as a consequence of changing patterns of erosion and deposition

Table 2 Examples of potential direct and indirect impacts on geoheritage and ecosystem services provided by geoheritage features and processes in PCAs arising from the effects of climate change

Climate change induced effects	Potential direct impacts on geoheritage from climate change induced effects	Potential indirect impacts on geoheritage from human responses	Potential impacts on ecosystem services provided by geoheritage features and processes
Coastal change: rising sea levels, increased storminess, and changes in patterns and intensity of coastal erosion and deposition	•Degradation or loss of exposures and landforms •Increased risk of accelerated coastal erosion, steepening and retreat; coastal squeeze where hard structures impede retreat •Changes in sedimentation patterns and dominant erosion/deposition processes, resulting in change or relocation of landforms and coastal re-shaping and realignment •Loss of beaches and saltmarshes if insufficient space, time or sediment supply for coastal readjustment •Enhanced landslide or rockfall activity on cliff coasts due to undercutting	•Demands for new or extended coastal defences that interrupt connectivity between sediment sources and sinks reducing sediment supply to beaches, sand dunes and saltmarshes, leading to loss of these features, coastal steepening, enhanced coastal erosion down-drift and disruption of geomorphological processes •Concealment of cliff and foreshore exposures behind coast defences •Concealment of foreshore exposures where groynes are used to trap sand	•Regulating: increased risk of coastal erosion and flooding; hard interventions disrupt regulating role of natural processes and landforms; loss or reduction of blue carbon sequestration •Supporting: habitat changes, readjustments, relocations and possible losses; may be exacerbated by hard coastal defences where natural processes are disrupted; possible biodiversity benefits from increased landscape heterogeneity/geodiversity •Cultural: deterioration or loss of aesthetic and inspiration value, recreation space, people's sense of place and geotourism assets; increased hazards for geotourism at coastal sites; loss of Earth history knowledge where exposures or landforms damaged or destroyed; gain of increased geodiversity
Fluvial adjustments: changes in flow regimes, increased flooding, and changes in patterns of erosion and deposition	•Degradation or loss of exposures and landforms •Increased river channel mobility and instability due to increased frequency of high flows and floods, and less readjustment time between floods •Increased channel scour, bank erosion and gullying •Seasonal changes in river flow regimes due to changed snow accumulation and glacier melting •Increased duration and occurrence of droughts, low river flows and non-perennial streams •Changes in cave hydrology and sedimentation	•Hard engineering responses resulting in: loss of visibility and access; disruption of geomorphological processes and interruption of connectivity between sediment sources and sinks; consequent downstream impacts on landforms and processes •Increased tree planting in catchments as a flood mitigation measure reduces stream dynamism and may moderate flood peaks and consequently some river processes	•Provisioning: seasonal reduction in freshwater supply •Regulating: increased risk of erosion and flooding; hard interventions disrupt regulating role of natural processes and landforms •Supporting: habitat changes, readjustments, relocations and possible losses; may be increased by hard interventions where natural processes are disrupted; possible biodiversity benefits from increased landscape heterogeneity/geodiversity •Cultural: deterioration or loss of aesthetic and inspiration value, recreation space, people's sense of place and geotourism assets; increased hazards for geotourism; loss of Earth history knowledge where exposures or landforms damaged or destroyed; gain of increased geodiversity

Table 2 (continued)

Climate change induced effects	Potential direct impacts on geoheritage from climate change induced effects	Potential indirect impacts on geoheritage from human responses	Potential impacts on ecosystem services provided by geoheritage features and processes
Soil moisture and groundwater changes: changes in soil moisture and groundwater level, or changes in chemistry such as salinity	•Lowered groundwater levels resulting in desiccation and damage to water-saturated organic deposit preservation •Higher antecedent soil moisture increasing flood and slope failure risk •Increased landslide activity, debris flows, accelerated soil erosion and sediment transfer to rivers •Aeolian desiccation of regolith, and increased frequency and extent of aeolian process on land •Increased aridity and desertification •Increased salinization altering the decomposition rate of soil organic carbon in coastal wetlands	•Surface desiccation may lead to increased demand for irrigation, putting pressure on groundwater resources and exacerbating issues relating to lowered groundwater •Demands for rewetting when there is limited or no water availability might lead to installation of large-scale water pipe systems •Increased salinization of soils from irrigation and rising sea level	•Provisioning: seasonal reduction in groundwater supply; loss or reduction of carbon sequestration from erosion of organic soils •Regulating: increased slope failure risk •Supporting: habitat changes, readjustments and possible losses or deterioration (from increased sedimentation in streams); may be increased by hard interventions where natural processes are disrupted; biodiversity benefits from increased landscape heterogeneity/geodiversity •Cultural: deterioration or loss of aesthetic and inspiration value, recreation space, people's sense of place and geotourism assets; loss of Earth history knowledge where exposures or landforms damaged or destroyed; gain of increased geodiversity
Cryosphere changes: reduced snow accumulation, accelerated glacier melting, increased thawing of permafrost	•Changes in mountain systems from snowmelt-driven to rainfall-driven hydrology •Changes in seasonal snowmelt patterns and snowmelt floods •Accelerated glacier retreat and disappearance of mountain glaciers and permanent ice from ice caves •Expansion of glacial lakes and increased risk of glacial lake outburst floods (GLOFS) from large ice avalanches, landslides and moraine dam failures •Thawing of mountain and arctic permafrost, resulting in increasing slope instability, slumping, coastal erosion, rockfalls and landslides •Decreased periglacial activity and loss or degradation of active periglacial landforms •Thawing and slumping of ice-cored moraines •Formation of new proglacial landform assemblages	•Changes in meltwater discharge and increased slope instability may increase demand for hard engineering resulting in loss of visibility and interruption to geomorphological processes	•Provisioning: seasonal reduction in freshwater supply •Regulating: increased risk of natural hazards; loss of sequestrated permafrost peat carbon •Supporting: habitat changes, readjustments and possible losses; may be increased by hard interventions where natural processes are disrupted; appearance of new proglacial ecosystems and possible biodiversity benefits from increased landscape heterogeneity/geodiversity •Cultural: glacier recession resulting in deterioration or loss of aesthetic and inspiration value, recreation space, people's sense of place and geotourism assets; increased hazards for geotourism; appearance of new visitor attractions (e.g. glacier lakes); loss of glaciers demonstrating reality of climate change; more difficult access to mountains, trails and mountain huts; loss of Earth history knowledge where exposures or landforms damaged or destroyed; gain of increased geodiversity

Table 2 (continued)

Climate change induced effects	Potential direct impacts on geoheritage from climate change induced effects	Potential indirect impacts on geoheritage from human responses	Potential impacts on ecosystem services provided by geoheritage features and processes
Sub-aerial weathering and erosion rate changes: changes due to increases in temperature and rainfall extremes	•Increased rates of physical, chemical and biological weathering •Degradation of rock outcrops and enhanced accumulation of talus at the base of rock faces or soft-sediment exposures obscuring the interest •Deterioration of building stone geoheritage	•Increased erosion rates may lead to stabilization works reducing visibility and access	•Regulating: increased slope failure risk •Supporting: habitat changes, readjustments, relocations and possible losses •Cultural: deterioration or loss of aesthetic value, recreation space, people's sense of place and geotourism assets; loss of Earth history knowledge where exposures or landforms damaged or destroyed; gain of increased geodiversity
Vegetation changes: increased or decreased vegetation growth	•Increased vegetation cover leading to: loss of visibility of exposures and landforms or physical damage due to root penetration; stabilisation of dynamic river and coastal process systems and periglacial processes on mountains •Decreased vegetation cover during droughts or as a consequence of wildfires leading to: accelerated erosion of mineral and organic (peat) soils, gullying and sediment transfer to rivers during precipitation events; erosion or burial of rock outcrops from increased soil erosion and aeolian activity; increased sedimentation in caves and karst depressions	•Changes in land use may result from vegetation changes, and alter sediment/water discharges affecting water-dependent features •Tree planting and/or land reclamation for food production may obscure features or result in root damage •Increased soil erosion from land use changes leading to increased sedimentation in caves and karst depressions	•Regulating: changes in water quality; loss or reduction of carbon sequestration from erosion of organic soils •Cultural: deterioration or loss of aesthetic value, recreation space, people's sense of place and geotourism assets; loss of Earth history knowledge where exposures or landforms damaged or destroyed; gain of increased geodiversity
Wildlife changes: changes in species present or their behaviours	•Changes in the presence or absence of burrowing animals may impact soft-sediment features •Introduction of environmental architect species (e.g. beavers) may impact fluvial or other processes •Changes in abundance of grazing species will impact vegetation growth and soil erosion susceptibility	•Introduction of protection against the impacts of new species or behaviours (e.g. reinforcing soft-sediment exposures to prevent burrowing) may obscure visibility and access •Restricting wild animal movements from cultivated land may increase their concentrations in sensitive geoheritage areas	•Regulating: changes in water quality; loss or reduction of carbon sequestration from erosion of organic soils •Cultural: deterioration or loss of geotourism assets and Earth history knowledge where exposures or landforms are damaged or destroyed

(Brazier et al. 2012). For example, in mountain environments, streamflow will change from primarily snowmelt driven, with peak flows occurring in spring and early summer and modulated by melting rates, to primarily rainfall driven, with peak flows during the rainy season and with higher peak streamflows. Enhanced erosion may lead to loss of some geoheritage features, such as important rock or sediment units of limited extent, but may also have benefits in providing new exposures in more extensive units. Additionally, some exposures and landforms at the coast and along rivers may be repositioned by changing patterns of erosion and deposition. Some features and processes of interest may shift location outside PCA boundaries, for example as rivers, coasts and estuaries adjust to climatically driven changes in processes of erosion and deposition. Cave and karst systems are particularly at risk from changes in hydrology arising from increased precipitation and flooding or incidence of droughts, and to increased soil erosion from more intense precipitation and loss of vegetation (He et al. 2021; Gillieson et al. 2022). Consequences include increased sedimentation in caves, potential blocking of passageways and contamination of speleothems, with loss of aesthetic value in show caves.

There will also be *indirect* impacts on geoheritage from human responses to climate change (Table 2), including changes in land use, and to increased natural hazards, with demands for coast protection and river management to mitigate erosion and flooding, that in some places may represent the greatest threat to geoheritage (Prosser et al. 2010). Where responses involve emplacement of heavily engineered structures to protect infrastructure and property, industrial and commercial areas and recreational space, rock and sediment exposures may be sealed by hard protection structures along coasts or river banks, while there may be catchment-scale and coastal-scale changes and knock-on effects (e.g. erosion of beaches and dunes that no longer receive sediment supply from newly armoured coastal sections). Changes in land use (e.g. afforestation to enhance carbon capture and offsetting or to mitigate flooding) may affect visibility, access and also geomorphological processes through changes in sediment/water discharges into rivers and cave systems.

A further consideration for managers of geoheritage in PCAs is the impact on visitor experience and safety from the effects of climate change. Of greatest concern is the risk of increased hazards, particularly where sites have high value for visitors, education and geotourism (Brocx and Semeniuk 2019). These hazards include rockfalls, landslides and slope failures precipitated by thawing permafrost or increased heavy rainfall, making access difficult and dangerous, particularly in mountain areas on hiking or access trails (Brandolini and Pelfini 2010; Bollati et al. 2013). There may also be significant impacts on hydrological systems and ecosystem services downvalley, and hydrological changes in glacier meltwater-fed rivers once deglaciation is complete (IPCC 2019). Where glacier retreat is accompanied by lake formation or expansion, there is enhanced risk of glacial lake outburst floods triggered by rock or ice avalanches, with cascading effects at lower elevations. As well as increasing hazards, deglaciation may also impact visitor experience by decreasing the scenic and aesthetic quality of landscapes as glaciers diminish and become increasingly covered in rock debris (Wang and Zhou 2019), or disappear entirely. This is likely in most of the world's mountain ranges in the next few decades and is already happening, for example, in Iceland, the Pyrenees and Glacier National Park in the USA. It is also a major concern for tropical mountain glaciers such as those in East Africa and Australasia, representing a significant loss of geoheritage (Bosson et al. 2019; Čekada et al. 2020; Vidaller et al. 2021) and the framing of such glaciers as 'endangered species' (Jackson 2015). There will be challenges for interpretation of these changes and making them meaningful to local residents and visitors (Rasmussen 2018). Although the retreat of glaciers has an important educational role in demonstrating the reality of climate change (Reynard and Coratza 2016; Purdie et al. 2020), it is already having an impact on tourism as well as loss of geoheritage, with a 'last chance' opportunity evident in visitor motivation (Lemieux et al. 2018; Welling et al. 2020; Salim et al. 2021a; Marr et al. 2022). On the other hand, new attractions, such as glacier lakes with icebergs, may appear (Reynard 2021), as evidenced at the outlet glaciers on the southern side of the Vatnajökull ice cap in Iceland. At the coast, sea-level rise, increased storminess and heightened risk of rockfalls and landslides from adjacent cliffs may compromise access for education and geotourism (Brocx and Semeniuk 2019; Fig. 1c). In semi-arid areas, increasing temperatures in summer and flooding in winter will directly affect geotourism sites through accelerated weathering, erosion and desertification, and represent additional risks to visitors (AbdelMaksoud et al. 2019; Berred and Berred 2021). Paradoxically, natural weathering and erosion have often created natural geomorphological features (unusual rock outcrops) that capture the attention of visitors. There will also be risk to geo-cultural heritage through damage to exposed rock carvings and paintings. In addition, interpretation will need to be updated to reflect climate change and its consequences, with greater emphasis placed on the dynamic landscape rather than just protection/preservation of static interests.

Geoheritage and geodiversity in PCAs provide many valued ecosystem or geosystem services (Gray 2013; Gray et al. 2013). Many of the direct and indirect impacts of climate change noted above will be mirrored in changes to these services mostly with consequent disbenefits for society and the environment (Table 2), which should be factored into impact assessments and priorities for adaptive management.

Step 4: Determining the Risk of Degradation The fourth step is to determine the risk of degradation of geosite value (scientific, educational, cultural, aesthetic and ecological) from the impacts of climate change on each geosite feature and process. Risk is defined as exposure to a range of environmental pressures and the threats arising from human responses, which have the potential to degrade, or cause damage to, the geoheritage value, or significance, of a geosite. Assessment of risk must combine the likelihood of detrimental change occurring due to each hazard or threat, and the likely severity of the consequences if change does occur. Common terminology when defining risk of degradation includes 'sensitivity', 'fragility' and 'vulnerability'. However, these terms have been defined in different ways in different disciplines and in the geoconservation literature (García-Ortiz et al. 2014; Selmi et al. 2022). To avoid confusion, therefore, we here define risk of degradation, after Wignall et al. (2018), as a function of the likelihood of climate change affecting a geosite, or affecting specific geosite features or processes, and the predicted severity of impact on geosite value if change does occur.

Likelihood of climate change affecting geosite features or processes depends on the magnitude of the pressure or driver, the exposure of the geosite to the pressure or driver, and the susceptibility and resistance of the geosite features and processes to detrimental change as a result of the pressure or driver. The magnitude of any aspect of climate change is likely to be constant across the area of many PCAs, and may be assessed from downscaled climate change projections. However, there may be variation if very large areas are being considered. In general, aspects of climate change identified as likely to impact geosites will be those with high or moderate magnitudes. The level of exposure of the geosite to the impacts of climate change, including both gradual changes, such as sea-level rise or glacier retreat, and changes in the frequency and magnitude of extreme events, such as storms and floods, will essentially depend on the location of the geosite. Its proximity to water and ice bodies such as coasts, rivers and glaciers that are likely to respond strongly to climate change, will be particularly important, although its latitude, longitude, altitude, aspect and slope may also be relevant. Exposure to potentially harmful change is sometimes referred to as a geosite's 'vulnerability' (García-Ortiz et al. 2014; Selmi et al. 2022), although this term is also used with alternative meanings (Fuertes-Gutiérrez and Fernández-Martínez 2010; Brilha 2016). Whether an environmental change in a PCA will result in a change to a geosite feature or process will depend on how susceptible the feature is to change in its environment. Active periglacial interests displaying patterned ground, for example, will be highly susceptible to reductions in freeze–thaw activity, and may become relict and degrade over time, but these same changes may have relatively little impact on key aspects of rock exposure sites (e.g. visibility, extent or composition). For features and processes with low susceptibility, the observed climate-related change at the site could be large, but the effect be negligible. The resistance of a feature or process to change will also play a part in how likely change is to occur. For those with high resistance, increasing climate-related change at the site will affect the interests, but the effect will be small and only increase slowly. Resistance is also a factor in how severe the impact will be if change does occur, as discussed below.

Predicted severity of impact will depend on the 'adaptive capacity' of geosite features and processes, also variously referred to as 'fragility' (Fassoulas et al. 2012), or 'sensitivity' (Brazier and Werritty 1994; Gray 2013); however, both the latter terms are also used with alternative meanings (e.g. Fuertes-Gutiérrez and Fernández-Martínez 2010; García-Ortiz et al. 2014; Brilha, 2016). Adaptive capacity is a geosite's degree of resistance to irreversible detrimental change from pressures or stresses, combined with its resilience in absorbing change and recovering from damage. By analogy with biodiversity conservation (Kittel 2013), adaptive capacity of geoheritage interests may be defined as the capacity of features and processes to cope with environmental change in situ, without loss of favourable condition, and is reflected in their ability to resist change (resistance) and to absorb and recover from disturbance (resilience). Adaptive capacity is assessed in terms of the characteristics that enable resistance (e.g. presence of hard rock features) and resilience (e.g. active geomorphological systems which may be able to adjust and evolve in response to climate stress). Some geosites will have a greater adaptive capacity than others depending on their intrinsic characteristics, and different geosite features and processes in the same area may display different degrees of resistance and resilience to damage under a similar degree of exposure to stress. Robust geosite features and processes will have a high ability to resist change, such as the slow erosion of a hard rock feature; but a finite extent and easily erodible material would make a feature less resistant (e.g. a fossiliferous shale bed or a Pleistocene interglacial deposit) (Fig. 1b). In some cases, once change occurs, resistance can also change. For example, a catastrophic rockfall could destabilise a cliff resulting in further rockfall and increased erosion rates. Some geosites will be able to absorb pressures and stresses, with the feature or process changing but with no detrimental impacts (e.g. decreased river flow resulting in a slower rate of channel change but no fundamental shift in river dynamics; or an extensive soft sediment exposure where a moderate increase in erosion does not detrimentally impact the value of the exposed sediment sections). Active systems may also be able to recover from detrimental change as part of the continued operation of natural processes (e.g. a beach system where longshore drift can replenish loss of sand). Such robust active systems will remain stable within extrinsic thresholds, absorbing or recovering from stresses and with an ability to renew landforms (e.g. river gravel bars), while sensitive systems may cross extrinsic thresholds or tipping points and be unable to recover (Brazier and Werritty 1994). In the latter case, the system may change irreversibly or be left in a state of perpetual readjustment and instability, such as changes in sinuosity of a river system responding to increased sediment load from accelerated erosion upstream (Brazier and Werritty 1994), or a river basin with multiple stable states switching to a persistently low run-off state (Peterson et al. 2021).

Assessments of adaptive capacity can usefully be informed by learning from past changes preserved in landform and sediment records in the landscape (Thomas 2012; Fryirs 2017). Understanding landscape history and past changes in slope stability, sediment production, landform distributions, floodplain and wetland histories, flood records and coastal changes can all help to inform landscape response models. Such assessments can also provide pointers for scenario modelling of future responses, landscape trajectories and identification of pressure points and areas at risk, and improve understanding of how geomorphological systems will adapt to the speed and scale of projected climate changes (Gray et al. 2013; Hansom et al. 2017; Skirrow et al. 2021). However, while indicative, the past may not provide exact geomorphological analogues for the future (Fryirs and Brierley 2021). For example, sea-level rise combined with reduced sediment availability and space constraints may be too rapid to allow existing coastal landforms to fully adapt in their present forms and locations, resulting in widespread coastal reorganisation (Orford and Pethick 2006; Cooper et al. 2020).

The overall risk of degradation of a geosite feature or process from climate change impact drivers can be established by identifying the likelihood and severity of damage from each identified climate change impact driver separately, using standard risk assessment procedures of combining likelihood of occurrence of change (in this case, likelihood of climate change affecting a geosite, feature or process) and predicted severity of impact (based on the adaptive capacity of the geosite feature or process) to give a relative risk rating from high to low (Wignall et al. 2018). The resulting climate change risk rating data will then indicate where the greatest management responses are likely to be needed, and also the cause of greatest risk from climate change at any geosite, which will aid identification of appropriate management and adaptation (Wignall et al. 2018). Higher risk categories are likely to represent an unacceptable level of risk requiring priority adaptation action; medium risk categories may require interventions to reduce the risk; and lower risk categories may represent acceptable risk but require regular monitoring.

Technical understanding of the types and rates of climate change and their effects on the features and processes of geoheritage interest and their significance will be necessary. Many PCA managers will not have the necessary expertise and will need expert help from central agencies, academic specialists or consultants. This will inevitably add to the cost of the assessments, but is essential if management decisions are to be well informed.

Adaptation Planning and Implementation

Step 5: Management Options and Contingency Planning The fifth step is to identify and assess management options and undertake contingency planning for their implementation as part of PCA action planning (see Nelson et al. 2020 and National Park Service 2021 for more detailed treatments). For geoheritage, management options range from non-intervention (‘do nothing’) to various levels of intervention depending on the particular situation and types of geosite (Sharples 2011; Wignall et al. 2018; Table 3). Broadly, these options include elements of (i) minimising change and preserving existing interests by reducing climate risks and other pressures; (ii) building resistance and resilience to survive change; and iii) dynamic adaptation that accepts and accommodates transformative change (Jackson 2021; Munera-Roldan et al. 2022). Note that the management options are not necessarily exclusive, and more than one option may be required and justified for part or the whole of a PCA.

At the landscape scale (e.g. whole mountain regions or river catchments), management interventions may be impractical, ineffective or too costly. The natural dynamics of land systems should simply be allowed to evolve without intervention under a stable or changing climate with an emphasis on managing the consequences of change. This non-intervention (or 'do nothing') approach was advocated for the Tasmanian Wilderness World Heritage Area (Sharples 2011) and will be more straightforward where human activity and infrastructure are absent and there is space for the systems to adapt (Bollati et al. 2017; Fig. 1e). As part of this approach, low-intensity monitoring (e.g. using remote sensing) should be implemented to document changes in geoheritage interests. Where the changes impinge on human activities, it may be necessary to create space and adapt to the consequences of more active geomorphological processes (e.g. relocating tracks, trails, buildings and visitor access routes or removing existing

Table 3 Adaptation options and actions for geosites at risk from climate change. (Adapted from Sharples 2011; Brown et al. 2012; Wignall et al. 2018)

Adaptation options	Actions
Non-intervention (do nothing)	Allow natural systems to evolve freely without intervention. Conduct low-intensity monitoring of changes (e.g. through remote sensing)
Work with nature	Implement nature-based solutions or 'soft' forms of intervention (e.g. managed realignment of the coast, beach nourishment, restoration of coastal landforms and habitats such as saltmarshes, mudflats and sand dunes, reconnecting rivers and their floodplains to enable floodplain/wetland restoration and increasing floodplain storage of floodwaters)
Revision of PCA boundaries	Modify existing PCA boundaries where the location of the feature or process has changed (e.g. as a consequence of coastal retreat or river channel migration). This will apply where existing PCA boundaries are tightly circumscribed. Larger PCAs may be required to accommodate the scale and nature of changes. In some cases, existing PCA boundaries will become unjustifiable
Proactive management	Implement proactive measures (e.g. pre-emptive tree felling, managed re-alignment of the coast, river restoration, slope stabilisation through woodland regeneration, re-routing access and re-locating buildings and infrastructure)
Prevent or minimise non-climate stressors	Identify and eliminate or reduce non-climate stressors (e.g. development, mineral extraction, grazing or visitor pressure)
Replacement exposures and geosites	For features at risk of degradation, identify options for replacement exposures or geosites in, and beyond, the current site boundary Restore previously exposed or degraded sites
Rescue and/or posterity recording and research	Research, document and record for posterity those geosites where the interest will be unavoidably lost or become inaccessible, and/or rescue and archive material for ex situ conservation (e.g. in museum collections) where appropriate
Hard intervention	As a last resort, install hard protection or burial in exceptional cases where finite or unique sites of exceptional value are threatened
Liaison, engagement, awareness raising and partnership working with stakeholders and others to integrate geoheritage in adaptation strategies and climate action plans	Liaise with planning authorities regarding geosite features and processes that climate change impacts will put at risk from planning-controlled activities (e.g. features squeezed between rising sea-level and new coastal infrastructure or defences) and assist in developing appropriate action plans; influence proactive planning and reactive responses Develop partnership working to address other stakeholder interests, as appropriate Liaise with the academic community, museums and the voluntary sector to undertake or assist scenario modelling, monitoring, research, rescue or posterity recording where appropriate Promote best practice in geoconservation and the benefits of nature-based solutions, such as 'leaving space for nature', avoidance of hard coastal and river engineering, and understanding the role of river and coastal processes in sediment transport and the maintenance of natural forms of protection (e.g. beaches, dunes and saltmarshes) Build geoconservation capacity of PCA managers through training and outreach
Update or replace the site interpretation	For geosites with changing features and processes, update or replace the provision of interpretation and education/communication to explain the changes and management actions undertaken

barriers). This may require extending site boundaries to accommodate mobile geomorphological systems or establishing new PCAs to encompass the evolving relocations of the geoheritage interests. For example, removal of barriers to coastal sediment movement may enable re-creation of new landforms and habitats by longshore extension as well as by landward migration (Nordstrom and Jackson 2013). It may also mean accepting the loss of particular landforms due to changes in dominant processes (Brazier et al. 2012). This requires 'managing for change', both in evolutionary and spatial terms, rather than attempting to temporarily preserve the existing landscape.

In other cases, where management intervention is necessary to protect vital infrastructure or unique geoheritage of limited extent, nature-based solutions or 'soft' forms of intervention (e.g. managed realignment of the coast, beach nourishment, restoration of saltmarshes, mudflats and sand dunes, and floodplain and wetland creation) are recommended (Crofts et al. 2020; IPCC 2022). This applies to adaptation both within PCAs and outside them since measures applied elsewhere may impact on the PCAs due to geomorphological connectivity with the wider landscape. Working with nature in this way also maintains ecosystem services and provides benefits for biodiversity (Brazier et al. 2012; Gray et al. 2013; Cohen-Shacham et al. 2016), but requires operationalisation of novel concepts and principles (in relation to rivers, see Fryirs and Brierly 2021 and Brierly and Fryirs 2022). 'Fix and control' should be considered only as a last resort, especially where PCAs provide an opportunity to demonstrate what giving space for landforming processes can achieve for hazard reduction, such as using floodplains for flood storage. PCAs should typically allow greater scope for nature-based adaptation since available space is less likely to be restricted by essential human infrastructure than elsewhere. In undertaking any intervention, geomorphological connectivity at the landscape scale is a key consideration (Wohl et al. 2019). For example, changes to the management of headwater catchments (e.g. the implementation of natural woodland regeneration to mitigate flooding) can alter downstream water flow regimes and sediment transfer, which in turn may impact on fluvial geomorphology interests, cave systems and the sediment replenishment of coastal landforms.

More frequent management may be required to maintain visibility of, and access to, exposure sites. This might include targeted or small-scale vegetation or talus clearance, when needed. Where exposure sites are physically threatened, excavation of replicates may be considered where the interest is spatially extensive—applying the 'shift in space, persist in place' concept (Thurman et al. 2020). Where site interests are spatially finite, burial and re-excavation for research purposes may be an option in exceptional circumstances. Where this is not possible, or where conservation targets or favourable condition cannot be met, it may be necessary to offset the loss by recording for posterity (e.g. through photography, logging of exposures and 3D scanning of features), and, where appropriate, rescuing features, such as fossils, for ex situ curation in museum collections. Very occasionally, some form of hard installation may be considered as a last resort for geosite features or processes of exceptional value (e.g. construction of shelters for palaeontological localities at risk of degradation).

Visitor management in potentially hazardous environments will require careful planning from a health and safety viewpoint. As far as possible, and on cost grounds, low-impact measures should be a priority (e.g. re-routing access or re-siting interpretation facilities). In mountain areas, glacier tourism adaptation has mostly been reactive (Salim et al. 2021a); for example, through developing new trails, adding infrastructure such as bridges, closing viewpoints and changing or relocating activities. However, in the longer-term different strategies will be required (Salim et al. 2021b, c); for example, through the provision of alternative visitor attractions and activities such as glacier museums and glacier lake boating trips, as in south Iceland.

The indirect impacts of climate change on geoheritage resulting from human responses are a significant concern (Table 2). In the case of natural hazards where there are likely to be extreme effects, such as glacier lake outburst floods in populated valleys, engineering interventions may be essential to reduce risk (Fig. 1f). In other cases, the aim should be adoption of adaptive responses that work with geomorphological processes, and are based on understanding geomorphological connectivity at a landscape scale (e.g. the role of erosion in maintaining sediment supply on soft coasts). In some cases, there may also be conflicts with other conservation interests such as biodiversity and cultural heritage interests (e.g. loss of habitats or archaeological sites on eroding coasts where sediment supply and throughput would be interrupted by coast defences). However, while defending one locality on the coast, for example, may offer a short-term solution for sites of highest value, this may simply increase erosion on the adjacent coast, and in the longer term, relocation and/or rescue and record may be the only practical and cost-effective solution, but nevertheless requiring resources.

Where human lives and livelihoods or other conservation interests are affected, liaison with stakeholders will be essential to help embed geoconservation in solutions for adapting to climate change and to raise awareness of good practice. However, truly adaptive responses to climate change will require changes in society's perception of what adaptation means, and changes in negative attitudes to processes such as localised erosion and allowing floodplains to flood. It will undoubtedly be challenging to achieve political and social 'buy-in', particularly where properties or infrastructure on eroding cliff tops or on floodplains may be impacted by adaptive solutions. In such situations, geoheritage will be only one factor among a range of political, social, economic and psychological considerations that will need to be taken into account, but, in any case, in many situations the economic realities may demand that only adaptive, nature-based solutions are cost-effective in the long term (e.g. Gopalakrishnan et al. 2016; Hagedoorn et al. 2021). As part of developing holistic adaptive management, geoconservation considerations will therefore need to be convincingly argued and integrated with wider stakeholder engagement and strategic planning for climate change adaptation (Haasnoot et al. 2021; Sayers et al. 2022), requiring proactive efforts by the geoconservation and geoscience community (Prosser et al. 2010; Brown et al. 2012). An example of regional stakeholder engagement in strategic planning from the Lake Tahoe Basin in California, USA, provided in Gordon et al. (2022) illustrates how a regional planning organization (the California Tahoe Conservancy) sponsored a technical expert group and downscaled climate modelling focusing on the large lake in a granitic alpine basin with geoheritage and numerous other values. The technical group established the linkages between the key resources in the Tahoe Basin, taking a systems-based approach in assessing the basin's collective vulnerability and those actions that can provide multiple benefits. A systems-based approach also encouraged effective adaptation management through multi-jurisdictional cooperation among agencies.

Success in such planning can be measured when community members from many backgrounds come together to shape a common sense of place and develop a future vision grounded in respect for diversity of perspective (Mickel and Farrell 2021). Taking care of long-term geoheritage health and resilience is a highly complex enterprise. It cannot be separated from issues of social health and justice, economic well-being, cultural heritage, or ecological condition and change. The role of protected areas in responding to the need to build resilient natural systems demands that decision making goes beyond the PCA boundary. This is particularly true for geoconservation, which provides the physical part of the human and ecological systems. This need is leading to the creation of collaborative partnerships that include interested parties and agencies from multiple sectors focused on a specific landscape or type of geoheritage (Tormey 2022). Inevitably, however, these efforts will not always be successful and fall-back measures such as rescue and recording may need to be implemented, recognising the difficult choices and trade-offs that will be required (Prosser et al. 2010).

Step 6: Indicators and Site Condition Monitoring The sixth step is to identify key indicators for detrimental impacts and undertake site condition monitoring at appropriate intervals to provide evidence to trigger management interventions if required. To monitor the condition of geosite features and processes, data on the current state of the features and processes must be gathered, then the current state compared to the favourable baseline state (Wignall 2019; Wignall et al. 2022). This comparison is used to make a judgment on whether the current condition exceeds, equals or fails to meet the favourable baseline state. Where the condition fails to meet baseline state, this is a trigger for remedial management. There are many possible measurements that may be made to assess the state of geosite features and processes, including those of the International Union of Geological Sciences (IUGS) and similar 'geoindicators' (Berger and Iams 1996; Berger 1997, 1998; Welch 2002, 2003; Woo and Worboys 2019; Crofts et al. 2020). Site condition monitoring requires selecting those indicators specifically relating to aspects of the geosite feature or process that are relevant to its conservation objectives and therefore to its condition. Three broad aspects of geosite features and processes that may be used as condition indicators are: physical attributes (extent, composition, morphology), visibility and process dynamics (RPDC 2003; Wignall et al. 2018; Wignall 2019; Wignall et al. 2022; Table 4). The effects of individual stresses, such as vegetation growth or development, can also be used as condition indicators (Prosser et al. 2006; Wignall et al. 2022). In the UK, there has been a formal programme for monitoring the condition of geosites for over 20 years, with monitoring and reporting the responsibility of UK country government agencies (Wignall et al. 2022). On the other hand, less formal citizen science approaches can also provide early warning of threats or significant site condition deterioration. For example, in Spain, a national programme of site monitoring, 'Apadrina Una Roca' ('Adopt a Rock'), utilises volunteers to visit sites annually and report threats or incidents to the Geological Survey of Spain (http://www.igme.es/patrimonio/ApadrinaUnaRoca.htm), and CoastSnap beach monitoring is now established in a number of countries (https://www.coastsnap.com/) (Fig. 2).

Steps 7 and 8: Adaptation Implementation, Monitoring and Review The final steps are to implement management intervention, either through proactive measures for geosites at moderate to high risk of degradation, or where decision thresholds are triggered by site condition monitoring. Monitoring of changes to geosites and their features of interest is directly linked to the management process and the implementation of evidence-based responses. As for biodiversity, a key part of this process is setting thresholds for decision triggers, informed by value judgements (Cook et al. 2016; Hilton et al. 2022). Repeat monitoring at intervals appropriate for the type of site and its risk of degradation will enable review and evaluation of adaptation measures adopted and learning from the outcomes, bearing in mind the uncertainties inherent in climate projections and the responses of geosite features and processes. Application of the framework should also be repeated iteratively as part of adaptive planning if and when new scientific information about the site becomes available, revised downscaled climate scenarios are developed or if there is a change in site management, site condition or risk of degradation assessment. The conservation objectives may also need to be evaluated and adapted in response to observed changes. In some cases, where it is impractical or too costly to meet conservation targets or maintain sites in favourable condition, appropriate rescue and recording measures should be implemented.

Table 4 Recommended site condition monitoring attributes, generic targets and severity of detrimental impacts. (Adapted from Wignall et al. 2018; Wignall 2019)

Attribute	Description	Target for favourable condition	Severity of detrimental impact if feature affected		
			Low (favourable condition)	Medium (unfavourable condition)	High (partially/totally destroyed)
Physical attributes (extent, composition, morphology)	This attribute refers to the physical condition of the features that form the basis of the selection of the site, including the absence of disturbance, physical damage or fragmentation of the interests. The physical attributes of the key features include the extent, composition and structure of the features and, where relevant, their quantity and morphology. For active process sites, physical attributes also include the presence of landforms and other physical characteristics (e.g. erosion or deposition), which indicate that the processes remain active	The physical attributes of the key features and the physical integrity of the site remain intact and undamaged	No changes, or changes are not damaging to the feature	Any damage or deterioration is reversible, either through continued operation of natural processes or through appropriate management	All or part of the feature is irreversibly damaged or destroyed
Visibility	This attribute refers to the absence of concealment (e.g. from vegetation, talus build-up, engineering constructions or buildings) of the key features that form the basis for the selection of the site and whether suitable close-up and/or distant views are available and safely accessible	The key features of the site remain visible in close-up and distant views, as appropriate	No changes, or changes do not cause any decrease in visibility of the feature	Any loss of visibility is reversible either through continued operation of natural processes or through appropriate management	The visibility of all or part of the feature is irreversibly lost

Table 4 (continued)

Attribute	Description	Target for favourable condition	Severity of detrimental impact if feature affected		
			Low (favourable condition)	Medium (unfavourable condition)	High (partially/totally destroyed)
Process integrity	This attribute is monitored for active-process geomorphology features only. It refers to the capacity of the geomorphological processes that form the basis for the selection of the site to evolve naturally and unimpeded. There should be no artificial constraints (e.g. from coastal defences or river bank protection). Activities such as extraction of sand and gravel may also disrupt natural processes and are relevant to this attribute as well as to physical attributes. In addition, factors outside the site may also affect the process dynamics within it (e.g. installation of upstream dams on a river)	The natural geomorphological processes that are the key features of the site, including their levels of activity and spatial extent, are not disrupted or impeded	No changes, or changes do not impinge on the operation of natural processes that are aspects of the feature	Any disruption to natural processes that are aspects of the feature is reversible, either through continued operation of the natural processes or through appropriate management	Operation of natural processes that are aspects of the feature is irreversibly disrupted, reduced or adversely altered, or entirely ceases
Negative indicators	This attribute refers to the presence of any factors, activities or changes in the vicinity of the site that might adversely affect it in the future (e.g. dumping of waste, growth of self-seeded trees or enhanced erosion likely to lead to the demand for coastal defences). Negative indicators can be used to determine if a review of site management is required. Issues already affecting the other attributes above will also be relevant here if they are likely to require a review of site management to prevent them becoming ongoing issues	There are no activities or changes evident in the vicinity of the site that might in the future affect one or more of the above attributes			

Fig. 2 CoastSnap beach monitoring, Montrose, Scotland. Members of the public are invited to monitor coastal erosion which is resulting in the retreat of the sand dune cordon, a natural form of coast protection, impinging on the adjacent golf course and increasing the risk of coastal flooding inland through several low-level corridors through the dunes. Strategic planning requires a shift from short-term engineering solutions at the coastal edge to dynamic, adaptational land management inland to provide space for relocation of assets to risk-free sites and to accommodate migration of the beach and dunes landward of their present position. This will require partnership and co-operative effort between all agencies, infrastructure providers, non-governmental organisations and businesses with a coastal remit or interest and supported by a funding stream (Rennie et al. 2021a, b) (photo: John Gordon)

Throughout the adaptation process cycle, liaison will be essential with the academic community, geological surveys, museums and the voluntary sector to undertake or assist with inventory, risk assessment, scenario modelling, monitoring, research, rescue or posterity recording where appropriate.

Discussion

There is a lack of guidance for protected area managers on strategies and methods for dealing with the challenges of planning for, and adapting to, the impacts of climate change on geoheritage interests. For example, while many UNESCO Global Geoparks are engaged in climate change-related activities, their focus has been to raise public awareness of climate change and to implement mitigation and adaptation generally through sustainable activities, nature-based solutions, reducing natural disaster-related risks, encouraging behavioural change and establishing good environmental governance (Zhechkov et al. 2019; Lemon 2021; Silva 2021; UNESCO 2021). As a contribution from a geoheritage perspective to future-proofing area-based conservation (Maxwell et al. 2020), our approach focuses on assessment of risk of degradation from climate change to identify priority geosites, features and process systems for contingency planning, supported by site condition monitoring and a portfolio of adaptation strategies. Primarily, the latter should aim to safeguard geoheritage, but geoconservation adaptation should also, as far as possible, align with the wider nature conservation agenda and the paradigm of 'nature and people', recognising the wider values and benefits of 'working with nature' and contributing to the UN Sustainable Development Goals (Brilha et al. 2018; Gordon et al. 2018a, b; Schrodt et al. 2019). Furthermore, climate change adaptation for geoconservation should not be considered in isolation from other stressors but should be part of comprehensive management planning. The most effective geoconservation may be achieved by reducing the effects of other pressures such as from inappropriate development, land use or visitor numbers.

A key principle is to anticipate and plan for change despite the uncertainties in climate projections, impacts and geomorphological responses. In most cases, adaptive planning and management will be essential to respond to climate change impacts, with plans and management updated as part of an iterative process (Williams et al. 2009; Williams 2011). It will also be important to think at the landscape scale and in dynamic terms, and not necessarily static preservation of existing features and processes in the same places (cf Schlaepfer and Lawler 2022) (Fig. 2). Planning for change will also require dealing with controversial issues with wider societal implications, such as managed realignment of the coast and restoring river floodplain connections by removing flood barriers, which will require long-term planning at a broader spatial scale. In planning for change, van Kerkhoff et al. (2019) identify four conceptual transitions that will be required by PCA managers to future-proof nature conservation. These apply equally to geoconservation and may be paraphrased as follows: (i) accommodating change rather than resisting it through attempts to 'fix and control' dynamic features; (ii) focusing on ecosystem services and benefits for people and nature, as well as geoheritage goals, that may arise from adaptation (e.g. reduced flood risk from re-connecting rivers and their floodplains); (iii) recognising adaptation as a people-engagement issue as well as a scientific one and addressing the often contested social, economic and political issues of adaptation (e.g. of managed realignment of the coast); and (iv) shifting from problem-solving to ongoing learning where uncertainty is prevalent and societal values may change. As noted by Wilson et al. (2020), consideration throughout the planning cycle should be given to stakeholder participation, socio-economic issues of adaptation, the degree of uncertainty in climate projections, natural system responses and the effectiveness of management interventions.

Accommodating Change The portfolio of geoconservation strategies ranges from 'non-intervention' to planned interventions informed by the risk of degradation assessment and enhanced monitoring. Non-intervention is likely to apply in the case of large dynamic geomorphological systems where there is limited human presence and the only practical option is to allow these systems to evolve in response to the changing climate. Non-intervention, other than any existing site management, may also apply in the case of resistant geosites such as disused hard rock quarries, road cuttings or extensive areas of rock exposures (Fig. 1a). However, in both cases, scientific study and site condition monitoring should be implemented to record or detect changes. Planned interventions should aim to maintain or enhance the adaptive capacity of the sites and their features and processes of interest, including resistance and resilience, depending on the particular levels of threats, susceptibilities and conservation values and objectives; for example, enhancing resistance and resilience may suffice where threats and risk are low to moderate. Enhancing resistance could include local measures to increase the stability of soft sediment exposures through drainage improvements or enclosing highly valued and susceptible features within a protective structure or building (e.g. fossilised footprints and trackways). Resilience may be enhanced by reducing other, non-climate stressors (e.g. from grazing/trampling and visitor pressures), removing vegetation from rock exposures, restoring geomorphological connectivity and maintaining natural processes. This may require managing what happens outside PCAs at a catchment scale, for example to reduce sedimentation within cave systems. It may also require engaging with stakeholder interests at geotourism sites to control visitor numbers. Measures to enhance adaptive capacity may include extending the boundaries of individual PCAs to enable shifts in the positions of river systems or migration of coastal landforms, and the identification and protection of areas to where natural systems may migrate (e.g. saltmarsh regeneration in future sediment sinks). This may involve scenario modelling to identify where process systems may be activated (e.g. areas with high future exposure to process changes where new saltmarshes or braided rivers may appear). Other adaptation response measures may entail spreading the risk by improving the representation and replication of geoheritage features and processes across a network of PCAs, identifying and protecting potential replacement sites or restoring degraded sites with comparable interests where the threats and risk of degradation are lower.

Where interventions are necessary, these may involve reinstating a geological exposure degraded by slumping of soft sediments or obscured by vegetation growth. In the case of active geomorphological systems, preferred options are to work with nature and to adopt nature-based solutions as far as is practical both on environmental, economic and societal grounds. Such solutions include proactive measures that restore natural rivers (Opperman et al. 2009; Palmer et al. 2009), removing dams (East et al. 2015), using green infrastructure (Chávez et al. 2021), development of soft forms of coastal protection (living shorelines) to minimise erosion (Temmerman et al. 2013; Leo et al. 2019; Smith et al. 2020), and managed realignment at the coast (Haasnoot et al. 2021). Such measures require longer-term planning than short-term reactive responses to particular extreme weather events. Adaptation may mean accepting that some PCA geoconservation targets cannot be met and need to be reviewed; for example, it may not be possible to maintain the full diversity of landforms in a particular PCA if the natural processes become more or less active or if the natural system undergoes a major reorganisation. In some exceptional cases, limits to adaptation will require a 'no-regrets' approach and accepting loss where the thresholds for the survival of particular features in particular areas are, or are likely to be exceeded, such as the disappearance of small mountain glaciers in most of the world's mountain ranges or deactivation of periglacial processes. In such cases, pre-emptive research and recording should be implemented. On the other hand, new geoheritage features may arise through the creation of fresh landscapes (e.g. in front of retreating glaciers).

Ecosystem Services and Benefits Adaptation and intervention should be carried out in such a way as to minimise impacts on ecosystem services and where possible enhance them. Many changes in geomorphological processes will impact on biodiversity interests (Brazier et al. 2012), so that climate change action plans for nature conservation require integration of geoheritage and geodiversity (Comer et al. 2015). For example, sea-level rise may result in direct loss of habitat and geomorphological changes that are too rapid for existing coastal ecosystems to absorb (Orford and Pethick 2006; Hunter and Nibbelink 2017); glacier recession and permafrost thaw will alter landscape heterogeneity (Kirkbride and Deline 2018; Ruiz-Fernández et al. 2019; Oliva et al. 2020; Gobbi et al. 2021), and changes in catchment hydrology will alter water flow regimes and discharges of sediment with downstream consequences for habitat distributions and conditions (Thorp et al. 2010; Wohl and Iskin 2019; Kemper et al. 2022). Hence, where appropriate, geoheritage adaptations should be integrated with those for biodiversity as part of a 'conserving nature's stage' approach that includes protection for vital geodiversity functions, geomorphic connectivity, corridors and refugia (Anderson et al. 2014; Hunter and Nibbelink 2017; Carrasco et al. 2021). Maintaining geoheritage and geodiversity in PCAs and implementing adaptations to work with nature is a way of safeguarding ecosystems. Landscape-scale restoration of natural systems (e.g. by increasing connectivity of geomorphological processes between different landscape units) benefits not only dynamic geomorphological interests but may alleviate biodiversity loss (von Holle et al. 2020). While adaptation and intervention are most commonly expected to be in the nexus between geoheritage and ecosystem services, there may be other overlaps such as a geoheritage-based decision to allow bluffs on an eroding coastline to erode having an adverse effect on archaeological resources on the bluff tops (see Vousdoukas et al. 2022 for a World-Heritage context). The overlapping but sometimes competing resource needs and agency responsibilities require that decisions be made through a process that promotes communication and trust among agencies and the public so that technical decisions effectively and satisfactorily incorporate the priorities of those interested and affected parties (Gordon et al. 2022; Tormey 2022). Whole-landscape approaches can also help to place geosites in their wider context and enable identification of potential locations for replacement of degraded sites. Geomorphological and ecological restoration at the landscape scale should therefore proceed in tandem to deliver co-benefits.

Adaptation as a People Engagement as well as a Scientific Issue Adaptive capacity depends on social, economic and political determinants as well as physical factors, and is sometimes defined in terms of social organisation and the resources available to a community to reduce adverse impacts (IPCC 2022). Barriers to adaptation may include lack of scientific information and geoscience expertise to implement measures, lack of supporting policy or legislation, stakeholder resistance and lack of financial resources to adopt the strategies in Table 3. For example, there may be limited flexibility in terms of extending PCA boundaries and making space for natural processes to evolve unimpeded. Coastal realignment may be constrained by coastal squeeze due to the presence of infrastructure inland (Fig. 1d), and property or infrastructure may need to be abandoned or relocated. Costs and benefits of options will also need to be evaluated. New policies and regulations may be required in PCAs (e.g. regarding access and planning and development of resilient infrastructure to accommodate space for future changes). These non-scientific factors may therefore provide limits to adaptation (e.g. where high-value infrastructure is at risk), and, in turn, societal constraints on adaptive capacity will influence the assessment of risk of degradation and may constrain the adaptation options. Nevertheless, there may be opportunities in terms of environmental improvements and sustainability benefits from adoption of nature-based solutions (Dudley et al. 2010; Cohen-Shacham et al. 2016; IUCN 2020). Throughout the adaptation process, consultation and engagement with local stakeholders, integration of geoconservation measures into Local Climate Action Plans and access to resources will be required. This may be less of a problem in PCAs which should typically allow greater scope for nature-based solutions since available space is less likely to be restricted by essential human infrastructure than elsewhere. However, where such solutions are applied, they require 'the full engagement and consent of Indigenous Peoples and local communities in a way that respects their cultural and ecological rights' (Seddon et al. 2021). A further requirement will be liaison with planning authorities regarding geoheritage interests that climate change impacts will put at risk indirectly from planning-controlled activities (e.g. new or upgraded hard coast defences) and to assist in developing appropriate action plans (Prosser et al. 2010). Removal or mitigation of non-climate stressors similarly may require negotiation with other stakeholders.

Ongoing Learning in the Face of Uncertainty Specialist geoscience input will be required in combination with local knowledge, particularly in compiling geoheritage inventories and in assessing the risk of degradation of geosites and their features and processes. This applies especially in the case of active geomorphological systems and at the landscape scale where changes may be non-linear, with the potential for abrupt or exponential shifts in dominant processes (Skirrow et al. 2021). Assessment of the potential for such change and identification of tipping points will be challenging, but should be informed by an understanding of landscape history and geomorphological sensitivity, recognising that the landscape is an amalgam of inherited features with different geological and geomorphological properties and characteristics acquired under a range of past climate conditions. A further consideration is geomorphological connectivity within drainage catchments and coastal cells since changes in one part of a connected system will have impacts elsewhere, which may be non-linear (Bruneau et al. 2011; Knight and Harrison 2013; Wohl et al. 2019); for example, increased headwater slope erosion leading to changes in sediment transfer between hillslopes and river channels downstream (Lane et al. 2007; Milan and Schwendel 2021). Similarly, in assessing risk of degradation, it is essential to consider the potential amplification from human activities, such as land use changes, and the connections between human and natural systems at the landscape scale (e.g. to consider the effects on downstream geomorphology of headwater catchment afforestation as a flood mitigation strategy). Such interactions are likely to lead to regional variations in the exposure and, therefore, risk of degradation of similar geoheritage features, processes and types of geosite. Understanding the wider landscape and societal context is therefore a vital part of adaptation planning.

Inevitably in the face of uncertainty, adaptation will be an iterative process and require learning from practical experience. It will require clear communication between geoscientists and PCA managers, building the expertise and capacity of the latter through training and outreach. It will also require tools and resources to assist development of proactive responses to climate change and promoting best practice in geoconservation. At the same time, there will be a requirement to increase public awareness, education and outreach efforts, including among decision and policy makers, to promote the benefits of nature-based solutions, such as 'leaving space for nature', avoidance of hard coastal and river engineering, and understanding the role of river and coastal processes in sediment transport and the maintenance of natural forms of protection (e.g. beaches, dunes, saltmarshes and mangroves). Good case studies will be invaluable to assist the learning process, both in terms of practical methods and strategies and in terms of planning processes and procedures.

Conclusions

Climate change in conjunction with geological and geomorphological processes has produced many of the features valued today as part of our geoheritage and will continue to do so. However, the natural environment is affected not only by amplified changes in climate, but also by the human responses to it. Geoconservation practitioners need to identify what the risks to geoheritage are from both sources. Value judgements may have to be made about which geosites can continue to be conserved, when to intervene and the type of intervention required to most effectively conserve the sites and their features and processes. While valued geosites will continue to require conservation as records of events or processes in Earth's geological history, there will be particular challenges as natural systems evolve. This may mean accepting the loss or relocation of particular features and the emergence of new features in some areas, for example as glaciers retreat and as sediment sources and sinks adjust to changed process dynamics and where environmental changes are too fast or complex to preserve existing features in their current states or locations. In other cases, planned interventions may be necessary to protect unique or exceptional geoheritage features, irreplaceable pages in the book of Earth's history, and particularly where these are at risk from human responses to climate change. Climate change is also an additive pressure interacting with, or compounding, other anthropogenic pressures. Adaptive management may first require addressing and minimising these other pressures. In this paper we have therefore attempted to provide a framework that combines assessment of risk of degradation with adaptation actions. We have also attempted to address and integrate the potential impacts of the human responses to climate change since in many cases these will have greater impact (Prosser et al. 2010). The challenge is to develop adaptive solutions that meet the needs of both geoconservation and society. In this respect, nature-based solutions should as far as possible be prioritised (Cohen-Shacham et al. 2016; IUCN 2020). Furthermore, the conservation and sustainable management of geoheritage and geodiversity in PCAs should contribute to the protection of natural sinks and reservoirs of greenhouse gases and to maintaining the ecosystem integrity necessary to ensure the long-term stability and resilience of natural carbon sinks and reservoirs recognised by IUCN (2021) as a core strategy for climate change mitigation and adaptation. Nevertheless, institutional governance, logistic capacity and resource availability will present constraints as well as challenges (Prosser et al. 2010).

Key points to consider in climate-resilient management strategies for geoheritage in PCAs are the nature of the geoheritage interest and site characteristics and their different susceptibilities to climate stressors. Information will be required at the scale relevant to PCA managers to help implement adaptation, integrating downscaled climate projections with local geoheritage inventories and degradation risk assessments. To an extent, management planning may be guided by studies of past landscape evolution, but while the past may provide indicative trajectories, these are unlikely to be exact analogues for the future, particularly if higher greenhouse gas emission scenarios are realised. Adaptive planning and management that involve working with nature and are informed by monitoring of changes, which will be unpredictable in scale and effects, will therefore be an essential part of integrated PCA climate-resilient action plans. This will require greater consideration of cross-boundary effects from changes elsewhere in the landscape beyond the PCAs and the interactions of geomorphological changes with other interests within the PCAs such as biodiversity, cultural heritage and visitor attractions. In turn, this will entail a paradigm shift in future-looking geoconservation, involving a transition from conventional approaches of attempting to preserve fixed assets to more adaptable and dynamic approaches that both conserve geoheritage and plan for evolutionary change at a landscape scale. Our adaptation planning framework addresses these issues and aligns broadly with proposals for biodiversity adaptation (e.g. Mawdsley et al. 2009; Kittel 2013; Gross et al. 2016; Schlaepfer and Lawler 2022) and cultural heritage adaptation (Sesana et al. 2020), and they should be easily integrated within the range of existing conservation planning frameworks that include climate change adaptation (e.g. Gross et al. 2016; Schwartz et al. 2018), and in planning PCA networks, including marine protected areas (Wilson et al. 2020). In turn, this should enable the incorporation of geoheritage into PCA management plans and wider regional Climate Action Plans and societal adaptation, with added value for objectives such as enhancing carbon sequestration, biodiversity and ecosystem services, and mitigating natural hazards. To achieve this, PCA managers will need to ensure active engagement by geoconservation experts within their teams or through external contracting.

Finally, geoheritage is a global concern as part of the 'memory of the Earth', but as yet there is no systematic assessment or protection of globally important sites and areas; for example, coverage in the World Heritage site listing is partial and geographically unrepresentative for several key themes (McKeever and Narbonne 2021). In the face of climate change, there is an urgent need to identify and protect these global priority locations and to implement mitigation and adaptation measures for those deemed most at risk of degradation, before the their geoheritage interests are irreparably damaged or lost.

Acknowledgements The authors thank an anonymous reviewer for helpful suggestions that improved the manuscript.

Declarations

Conflict of Interest The authors declare no competing interests.

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