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Valuing the Quaternary – Nature conservation and geoheritage

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ABSTRACT

This paper introduces the Special Issue of the *Proceedings of the Geologists' Association* on 'Valuing the Quaternary – Nature Conservation and Geoheritage', arising from the International Union for Quaternary Research (INQUA) Congress in Dublin, in July 2019. It presents an overview of the values of Quaternary geoheritage, which merit recognition as an integral part of nature conservation, to protect priority sites and features for scientific research and education, and to deliver wider ecological, cultural and aesthetic benefits. The paper highlights the benefits of incorporating knowledge and understanding of Quaternary geoheritage for nature conservation and society. Palaeoenvironmental, palaeoecological and palaeobiological archives are a key source of ecological and environmental data that allow learning from the past to help address contemporary conservation challenges such as biodiversity loss, anthropogenic pressures and climate change. Quaternary science plays a vital part in supporting the wider nature conservation agenda, including strengthening the role of protected and conserved areas in the sustainable management of natural capital and ecosystem services, climate change adaptation, marine conservation, nature restoration and recovery, connecting people and nature and informing nature-based solutions to threats faced by society. However, challenges remain to achieve protection of key geoheritage sites and landscapes globally, and to integrate better understanding of geodiversity in nature conservation research, policy development and practice to help address the twin crises facing nature conservation – biodiversity loss and climate change. Quaternary studies provide temporal and spatial perspectives to inform forward-looking nature conservation that is dynamic rather than static in outlook.

1. Introduction

At the International Union for Quaternary Research (INQUA) Congress in Dublin, in July 2019, a session on 'Valuing the Quaternary – Nature Conservation and Geoheritage' formed part of the INQUA Commission programme on 'Humans and the Biosphere'. The presentations and posters in this session examined the importance of conserving and managing Quaternary geoheritage and the applications of Quaternary science to contemporary nature and heritage conservation issues. Key themes included strategies to conserve individual sites, the relationships between geoconservation and conservation of Lower–Middle Palaeolithic and more recent archaeology, Quaternary geoconservation audits and the application of palaeoecology to conserving the historic environment and priority habitats. These themes are reflected in the contributions to this Special Issue and include studies from the UK (Cunha et al., *this issue*; Dale et al., *this issue*; Dempster and Enlander, *this issue*; Hazell et al., *this issue*; Tisdall and Miller, *this issue*; White et al., *this issue*), Ireland (Hawthorne et al., *this issue*), Portugal (Cunha et al., *this issue*) and Turkey (Aytaç et al., *this issue*).

Geoconservation is primarily the practice of conserving geoheritage – those features, processes and/or elements of geodiversity that have special geological, geomorphological or pedological values (Burek and Prosser, 2008). It includes their conservation, enhancement and promotion through interpretation and education, usually in protected or conserved areas (Crofts et al., 2020). Geoconservation is part of *nature* conservation, as 'nature' includes inter-dependent biotic and abiotic systems of land, air and water environments. Nature conservation has been used inter-changeably with species conservation, but practical conservation has increasingly recognised the role of habitats, and therefore the underlying abiotic environment, as central to nature conservation success (Anderson et al., 2015, 2023; Bailey et al., 2022). At the same time, the conservation movement has started to acknowledge the value of geodiversity both for its own sake and for its wider values as set out in resolutions adopted by the International Union for Conservation of Nature (IUCN, 2008, 2012, 2020). The fundamental requirements for effective geoconservation in a region or country involve: (1) inventory of geoheritage interests and sites; (2) assessment of their values; (3) conservation management and protection; (4) monitoring; and, where

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appropriate, (5) interpretation and promotion (Brilha, 2016; Crofts et al., 2020). Quaternary landscapes, landforms and deposits are an integral part of geoheritage and, as such, merit conservation for their scientific, educational, ecological, cultural and aesthetic values (Brown et al., 2014; Gordon et al., 2019; Crofts et al., 2020). However, geoconservation has equally important and wider value in helping to sustain nature and people. Quaternary landscapes provide a rich and evolving variety of substrates, biogeochemical environments and a variety of morphological settings for nature and people (Hjort et al., 2015; Lawler et al., 2015). Quaternary landscapes also contain palaeoenvironmental, palaeoecological and palaeobiological archives which are a vital source of data to inform the conservation of contemporary and future biodiversity and enhance our understanding of the dynamic interactions between humans and their environments over time (Willis et al., 2007; Dearing et al., 2015; Birks, 2019; Fordham et al., 2020).

There has been growing recognition that Quaternary science has a significant role in supporting the delivery of key elements of the wider nature conservation agenda, including strengthening the role of protected and conserved areas in the sustainable management of natural capital and ecosystem services, climate-change adaptation, marine conservation, connecting people and nature, and informing natural solutions to challenges faced by society (Gray et al., 2013; Brilha et al., 2018; Gordon et al., 2018a). It can also make a potential contribution to nature restoration and recovery (Defra, 2022; UK Statutory Nature Conservation Bodies, 2022). This has been accompanied by advocacy for more holistic approaches to nature conservation, recognising that abiotic features and processes are a fundamental part of nature and natural diversity (Brilha et al., 2018; Chakraborty and Gray, 2020; Gordon et al., 2021; Tukiainen et al., 2022). At the same time, there is acknowledgement of the wider values of geoheritage and geodiversity for people and nature, and embracing ecosystem services, sustainable development and geotourism (Gordon, 2019; Gray, 2021). Quaternary science and geoconservation are also crucial for supporting the conservation of the historic environment (Last et al., 2013; Cunha et al., *this issue*; Dale et al., *this issue*; Hazell et al., *this issue*; White et al., *this issue*).

Conserving Quaternary geoheritage is essential to protect the stock of scientifically valuable field resources and museum collections for research and education. However, many Quaternary terrestrial and marine sites, and the archives of the past that they contain, are under increasing pressure and threats from human activities, including urbanisation, infrastructure development, land-use changes, mineral extraction, and coastal protection, as well as activities that disturb seabed geomorphology, sediments and processes, and from climate change (Crofts et al., 2020; Gordon et al., 2022). Lack of management, leading to vegetation encroachment and build-up of scree concealing and degrading Quaternary sections, sedimentary sequences, and landscapes is also significant. These pressures and threats are a matter of concern at a time of growing international recognition both of the need to take action to conserve Quaternary geoheritage, particularly as this is often overlooked in the development of policies relating to planning, nature conservation and the natural environment, and the importance of applied Quaternary science for nature conservation and environmental management (Gray et al., 2013; Chakraborty and Gray, 2020; Tukiainen and Bailey, 2022).

As an introduction to this Special Issue of the *Proceedings of the Geologists' Association* on 'Valuing the Quaternary – Nature Conservation and Geoheritage', this paper provides the context for the articles and a brief introduction to the values of Quaternary geoheritage. First, it reviews the different components of Quaternary geoheritage and why their conservation deserves recognition as an integral part of nature conservation, both from a geoconservation perspective and from wider ecological and biodiversity conservation viewpoints. Second, it examines the role of Quaternary science in supporting the developing nature conservation agenda. We have not compiled a comprehensive or systematic review of the topics covered, but rather highlight what we consider to be key issues and with reference to selected studies from the diverse literature.

2. Quaternary landforms and deposits: geoheritage values and geoconservation

2.1. Scientific value of Quaternary archives

Quaternary geoheritage constitutes an archive of the climatic, geomorphological and environmental changes that occurred during the last ~2.6 Ma of geological time. The Quaternary is subdivided into the Pleistocene (2.6 Ma–11,700 years BP) and the Holocene epochs (11,700 years BP to the present day). The Quaternary archive is preserved in a variety of terrestrial, freshwater, lacustrine and marine landforms and deposits. These record the profound changes that have occurred on decadal to millennial timescales and fundamentally shaped the geologically recent evolution of the present landscape and its associated biota (Lowe and Walker, 2014; Rull, 2020). This archive is represented *in situ* at a variety of spatial scales, from discrete sites comprising sequences of glacial and interglacial deposits (*e.g.*, at Marks Tey in Essex – Tye et al., 2016; and Pitstone Quarry, Marsworth – Murton et al., 2015) to peat bogs and lakes with Lateglacial and Holocene palaeoenvironmental records (*e.g.*, at Blelham Bog, Cumbria – Huddart, 2002; and Loch Ashik, Skye –Brooks et al., 2012), and from whole landscapes comprising assemblages of landforms and deposits (*e.g.*, the Parallel Roads of Glen Roy – Palmer, 2021; and the Cairngorm Mountains in Scotland – Gordon and Brazier, 2021), to *ex situ* museum collections of fossils, artefacts, other specimens and even archived sediments (*e.g.*, at Herne Bay Museum - Knowles, 2021; and Salisbury Museum, visited during the 2019 pre-INQUA field trip – Bridgland et al., 2019a; see also Cunha et al., *this issue* and White et al., *this issue*) (Fig. 1). The conservation of sites, landscapes, museum collections and museum specimens, which collectively represent key elements of Quaternary history, is an important component of conserving Earth's geoheritage. Moreover, conservation of these elements in protected and conserved areas also enables continued progress in scientific research and education, allowing the testing of new and emergent theories against critical field evidence in such diverse subject areas as long-term landscape evolution during the Cenozoic, the history of climate change and glaciation, relative sea-level changes, and Holocene geomorphological changes and landscape evolution (Gordon et al., 2019, 2021; Dempster and Enlander, *this issue*). For example, the study of Quaternary landforms and deposits has revealed the responsiveness of the environment to global climate changes in the past, the patterns of landscape evolution during the Quaternary (*e.g.*, Koster, 2005; Bridgland and Westaway, 2014; Gupta et al., 2017; García-Moreno et al., 2019; May, 2019), the history and dynamics of Pleistocene ice sheets (Rea et al., 2018; Fairbairn, 2022) and the responses of biota and geomorphological processes to climate change (Hoogakker et al., 2016; Ballantyne, 2019; Clark et al., 2022). Pollen records and radiocarbon dating of organic sediments in bogs have been used to establish the timing of Lateglacial glacier advances in Scotland and elsewhere (Lowe and Brazier, 2021), whilst pollen records of montane conifer genera have helped to constrain the elevation history of the northern Tibetan Plateau since the Middle Miocene (Miao et al., 2022). Some sites or areas have historical geoheritage value where key concepts or theories were developed (*e.g.*, Glen Roy, where Louis Agassiz in 1840 found compelling evidence to confirm the theory of ice age continental-scale glaciation). Furthermore, much of human evolution has taken place during the Quaternary (Galway-Witham et al., 2019). Consequently, Quaternary landforms and deposits provide the landscape context for human activities and, together with palaeoenvironmental records, reveal environmental opportunities, constraints and drivers of changes that have impacted these activities (Cotterill et al., 2017). Quaternary sites also provide context for historical archaeological collections (Cunha et al., *this issue*; Dale et al., *this issue*; White et al., *this issue*). Hence there are strong, mutually supporting links between conservation of geoheritage and Palaeolithic heritage (Last et al., 2013; Cunha et al., *this issue*; Dale et al., *this issue*; White et al., *this issue*). For the present, Holocene, interglacial, Quaternary deposits

Fig. 1. Selected examples demonstrating the range of Quaternary geoheritage interests and categories of site. (a) Coastal sections are a particularly important research and educational resource, especially where exposures are maintained by active marine erosion. Installation of hard coast defences enables the build-up of landslip debris and vegetation, partially or totally concealing the exposures until debris and vegetation are removed by storms. Soft coastal defences can increase the levels of the beach, which obscures the bottom of the cliff. At Mundesley Cliffs SSSI, Norfolk, a key locality for Middle Pleistocene glacial and interglacial deposits, hard defences were offset from the base of the cliff, allowing storms to clear the base of the cliff, and the Bacton sandscaping project has since raised the level of the beach at the eastern end of the site. The cliffs were surveyed before the sandscaping took place, and regular monitoring is taking place to understand the impact of the coastal defences on the SSSI. (b) A sequence of Middle Pleistocene deposits exposed in an active quarry at Leet Hill, Kirby Cane SSSI, Norfolk, comprises fluvial gravels overlain by glacial outwash gravels and sands. The exposures are periodically recorded *via* a watching brief agreed through mineral planning. Long-term conservation of exposures in soft sediments after working has ceased requires the agreement of a suitable restoration plan identifying conservation sections that can be periodically cleaned for research and demonstration purposes. (c) Pitstone Quarry SSSI, Marsworth, Buckinghamshire, displays evidence of two interglacial episodes, an intervening cold stage, and periglacial features with plant and animal remains indicating a sequence of temperate–periglacial–temperate environments and processes during the late Middle Pleistocene (MIS 7–5e). It is a former chalk quarry now restored and managed as a local nature reserve. Periodic vegetation clearance and excavation of talus are required to maintain demonstration exposures. (d) The Cairngorm Mountains are a classic landscape of selective linear glacial erosion. Relict non-glacial landforms (palaeosurfaces with tors, weathered rock and granite domes) that have generally been little modified by glacial erosion are juxtaposed with glacial troughs and breached watersheds, with glacial deposits in the corries and ice-marginal deglacial landforms in the valleys and on the lower slopes. The landforms and geomorphological processes of the Cairngorms support an internationally important biodiversity. (e) Glacifluvial landforms are vulnerable to quarrying which may provide sedimentological information if monitored during working but destroy the landform integrity. Carstairs Kames is an esker system and associated glacial meltwater deposits that form part of an extensive glacial drainage system in the Midland Valley of Scotland. A significant area of the landform assemblage was removed by quarrying in the past, but the core area is now protected as an SSSI. (f) The east flank of the Trotternish Ridge, Skye, contains the largest continuous area of landslides in Britain. Huge blocks of lava have been displaced by translational sliding along a failure plane in the underlying sedimentary rocks. The inner zone of the landslides is a labyrinth-like complex of tabular and tilted lava blocks, weathered pinnacles, buttresses and fantastic rock architecture. The site is a highly popular tourist attraction. (g) The lake basin and fringing bog at Loch Ashik SSSI, Skye, is a key reference site for interpreting palaeoenvironmental changes during the Lateglacial and early Holocene based on pollen and chironomid records. The latter, in particular, have enabled reconstruction of a high-resolution temperature record. The lacustrine deposits also contain tephra layers that provide chronostratigraphic marker horizons. (h) Raised beaches and other evidence at the coast reveal patterns of Quaternary sea-level change. Sub-fossil tree stumps exposed on the foreshore at Borth, Ceredigion, form part of a middle Holocene forest drowned subsequently by rising sea-level. (i) Display of Quaternary artefacts at Salisbury Museum for the INQUA Field Meeting, 'The Quaternary Fluvial Archives of the Major English Rivers', July 2019. Such *ex situ* artefacts and fossil materials are a significant part of Quaternary geoheritage, providing that they have been properly recorded and contextualised.
(Images: a–c, h, i Eleanor Brown; d–g John Gordon.)

include proxy records of the increasing environmental impacts, such as deforestation and soil erosion, arising from the activities of Neolithic and Mesolithic people (*e.g.*, Innes et al., 2013; Innes and Blackford, 2017; Edwards et al., 2019; Hazell et al., *this issue*). They also include proxy records of cultural heritage and landscape change (Hazell et al., *this issue*).

2.2. Terrestrial Quaternary sites for research and education

Future advances in Quaternary science depend on the availability of key sites and areas for research and education. These scientific and educational values are recognised in the inclusion of Quaternary interests in systematic inventories and conservation assessments of geoheritage sites, particularly in Europe. The latter include the Geological Conservation Review in Great Britain (Ellis, 2011; Brown et al., 2014), the Earth Science Conservation Review in Northern Ireland (Dempster and Enlander, *this issue*), the audited County Geological Sites (CGS) programme in Ireland (Gatley and Parkes, 2016; Parkes et al., 2020), the National Inventory of Geological Heritage in France (De Wever et al., 2015), the Spanish Inventory of Sites of Geological Interest (García-Cortés et al., 2019) and the national inventory of geoheritage in Portugal (Pereira et al., 2015). Such sites are an essential component of each country's nationally and internationally important geoheritage and form a key part of their natural assets. Such inventories are not a 'once-and-for-all' exercise but need to be reviewed and updated as the science progresses (Gordon et al., 2019; Dempster and Enlander, *this* *issue*). Individual countries have developed national geoheritage site inventories, and some internationally important sites are inscribed on the UNESCO World Heritage List or included within UNESCO Global Geoparks (Larwood et al., 2013). However, there is as yet no systematic international assessment of key geoheritage sites and landscapes.

2.3. Marine Quaternary sites and features

Whilst much of the conservation focus has been on terrestrial sites and features, the significance of marine geodiversity and geoheritage is now being recognised for the scientific interest of seabed landforms, sediments and processes, and for their role in supporting habitats and species in marine protected and conserved areas (Burek et al., 2013; Buhl-Mortensen et al., 2015; Gordon et al., 2016; Coratza et al., 2019). Notably also, marine sediments form significant sinks for organic carbon from terrestrial sources (Smeaton et al., 2021). Quaternary features of the seabed have been used as an additional and supporting factor in the selection and designation of Marine Protected Areas (MPAs) in Scottish territorial and offshore waters, for example. Here, the Marine (Scotland) Act 2010 and the Marine and Coastal Access Act 2009 have enabled the establishment of 36 Nature Conservation MPAs within Scottish territorial and offshore waters. Although these are designated primarily for biodiversity, they incorporate many geoheritage features which provided a strong supporting case. In addition, other existing protected area designations (*e.g.*, Special Areas of Conservation (SACs) and Special Protection Areas (SPAs)) that form part of the MPA network include key geoheritage areas. Practical and policy issues present challenges that demand a flexible approach to marine geoconservation involving integration with biodiversity management in existing protected areas, and elsewhere, for stand-alone measures to be based on evidence of the sensitivity and vulnerability of the interests present (Gordon et al., 2016).

2.4. Quaternary sites with cultural, aesthetic and spiritual values

Many Quaternary sites and landscapes have cultural, aesthetic and spiritual values (Reynard and Giusti, 2018; Reynard, 2020). Geomorphological processes, including glaciation, mass movement and coastal change, acting in concert with climate change and the underlying geology, have shaped the defining character of landscapes (Simensen et al., 2021). In Western cultures, distinctive natural features and landscapes have provided visitor attractions for tourism since the late 18th century (Hose, 2016; Migoń, 2016; Chylińska, 2019). Examples range from Uluru and the Twelve Apostles' sea stacks in Australia to the Rügen Cliffs on the Baltic coast of Germany, the Giant's Causeway coast in Northern Ireland and the Trotternish landslides in Scotland (Fig. 1f). In Eastern cultures, sacred mountains and waterfalls have been celebrated for over two millennia (Chen et al., 2015). Globally, many UNESCO Global Geoparks feature spectacular Quaternary landforms that underpin geotourism activities and sustainable economic development in partnership with local communities (Aytaç et al., *this issue*). Geoparks also have a wider role in promoting education and public understanding of geoheritage, which includes awareness of natural hazards and climate change. Spectacular landscapes and geomorphological features have also inspired art, poetry and literature in both Western and Eastern cultures (Gordon, 2018), whilst some natural features have strong spiritual or religious values (Kiernan, 2014). Others have close links with archaeology and human history, so that identifying geocultural connections can help to deliver multiple heritage conservation benefits (Sayama et al., 2022; Aytaç et al., *this issue*; Hazell et al., *this issue*).

2.5. Conservation and management issues in Quaternary sites

Quaternary features and interests occur as exposures of sediments in quarries and in coastal and river sections, as active and inactive landform systems and as sediment sequences within bogs and on lake floors (Fig. 1). They span exposure, integrity and finite site categories that present different conservation management challenges arising from various pressures and threats and consequently require a variety of different solutions (Bridgland, 2013; Prosser et al., 2018; Crofts et al., 2020; Evans et al., 2023). As exemplified in Northern Ireland (Dempster and Enlander, *this issue*) and Scotland (Tisdall and Miller, *this issue*), problems have arisen in relation to sand and gravel extraction where landform integrity is threatened, and conflicts between the needs of conservation and those of industry and development may need to be balanced in the national interest. Early engagement with stakeholders and planning authorities is essential to ensure that geoheritage interests are properly included in environmental impact assessments. This also requires dialogue and partnership working among the local community, landowners and managers, the statutory conservation agencies and the scientific community (Brazier et al., 2017). However, this is not always achieved, leading to loss of significant features as in the case of the Callander area in Scotland (Tisdall and Miller, *this issue*). On the other hand, many active sand and gravel quarries have been, and continue to be, invaluable sources of sedimentary evidence for reconstructing Quaternary environments, processes and chronologies (Rex et al., 2023). Positive outcomes can be achieved through monitoring and recording of sections exposed during working (*e.g.*, Harding et al., 2012), and by the creation of conservation sections during restoration (Fig. 1). Such issues should be addressed at an early stage of the planning process, emphasising the need for inclusion of geoconservation in national and local planning policies (Tisdall and Miller, *this issue*). Ground surveys for sustainable development can also contribute to geoheritage, geoarchaeology, geoscience and nature conservation. In the UK, there has been a long history of developer-funded research for geoarchaeology (*e.g.*, for the High Speed 1/Channel Tunnel Rail link – Bridgland et al., 2013; Wenban-Smith, 2013); examples of such initiatives are described by Cunha et al. (*this issue*) and White et al. (*this issue*). There is much to be gained from better and earlier collaboration between engineers, Quaternary scientists and archaeologists. This includes being able to use ground-survey data to plan mitigation for conservation (Brown, 2019), collect new geoscience or geoarchaeological data (White et al., *this issue*), or inform sustainable development which takes into account Quaternary geohazards such as unstable ground from past glacial, glacifluvial or periglacial activity (Giles et al., 2017; Griffiths and Martin, 2017; Moore et al., 2022).

Cunha et al. (*this issue*) compare geoconservation challenges for localities with Quaternary river sediment sequences associated with the River Thames in urban north Kent and south Essex to those for similar sequences associated with the River Tagus in Portugal. There are notable similarities and significant contrasts in both the science represented and the approaches to its dissemination, and to site protection and enhancement. These two fluvial sequences share a downstream setting, both being estuarine during sea-level highstands. Also in common is an overlap between Quaternary geological and archaeological (Lower–Middle Palaeolithic) interests. Differences stem from the climatic setting and the contrasting population and associated development pressures. A particular example site within the downstream Thames Quaternary coverage is the topic of the paper by White et al. (*this issue*) on Clacton-on-Sea (Clacton cliffs, foreshore and golf course). Clacton is a rare example of a British type locality of a Palaeolithic industry (the Clactonian), and of a Lower Palaeolithic site that has yielded artefacts fashioned from both wood and bone, in addition to the ubiquitous stone (flint) ones (White et al., *this issue*). This site, which does not have permanent exposures, is nonetheless of sufficient importance for statutory notification to have taken place (Bridgland, 1994).

Long-term preservation of soft-sediment sections is often problematic unless exposures are maintained by coastal or fluvial erosion (Fig. 1a). However, practical conservation techniques exist for conservation sections during restoration of quarries (Radley et al., 2013; Evans et al., 2023). Quaternary sites are also vulnerable to deterioration or loss through concealment by vegetation growth and talus accumulation, likely to be exacerbated by the effects of climate change (Wignall et al., 2018), and may require re-excavation for research and demonstration purposes (Bridgland, 2013) (Fig. 2a, b). Planting trees and re-foresting the landscape for biodiversity gain and climate-change mitigation may conflict with conserving the morphology and visibility of some Quaternary landforms (*e.g.*, moraines and eskers). However, whilst large-scale afforestation is generally incompatible with geomorphological conservation objectives, accommodating natural regeneration should be possible with careful management, including robust but varied grazing control and maintaining access to, and visibility of, key landforms, as part of integrated management of geodiversity and biodiversity (Crofts, 2019; Crofts et al., 2020). Exceptionally, where the interest is finite, installation of geotextile before burial may be an option as it facilitates re-excavation for research purposes, as at Swanscombe Skull Site SSSI/NNR (Fig. 2b) (Bridgland, 2013; Bridgland et al., 2019b). Geoconservation, therefore, does not end with site assessment and designation but requires ongoing management planning, including setting conservation objectives and 'favourable condition' criteria as part of site management and monitoring plans for protected and conserved areas (Prosser et al., 2018; Crofts et al., 2020).

2.6. Mechanisms of Quaternary site protection

At a national level, conservation of Quaternary and other geoheritage sites is delivered generally through a range of statutory and informal protected and conserved areas underpinned by various national or regional legislation and policies in different countries (*e.g.*, Wimbledon and Smith-Meyer, 2012; Crofts et al., 2020; Bétard et al., 2023; De Wever and Rouget, 2023; Cunha et al., *this issue*). For example, in the UK, conservation of Quaternary sites is delivered principally through statutory designation of Sites of Special Scientific Interest (SSSIs) in Great Britain and Areas of Special Scientific Interest (ASSIs) in Northern Ireland. Some sites may also be protected as National Nature Reserves (NNRs), an example being the Swanscombe Skull Site in the Lower Thames (see Cunha et al., *this issue*). At a local level, Local Geological Sites (England), Local Geodiversity Sites (Scotland) and Regionally Important Geodiversity Sites (Wales) are given discretionary protection by local planning authorities and the National Parks through the development planning system. In the case of very large sites, such as sand and gravel landscapes in lowland areas, there is a need for landscape-scale conservation mechanisms and consideration of how geoheritage interests might be better recognised and integrated into landscape conservation mechanisms such as Areas of Outstanding Natural Beauty (AONBs) and National Scenic Areas (NSAs) (Gordon et al., 2019; Dempster and Enlander, *this issue*). At an international level, some sites of 'outstanding universal value' are protected through World Heritage listing (McKeever and Narbonne, 2021), and others are informally conserved within UNESCO Global Geoparks and national geoparks.

3. Ecological and nature conservation values of Quaternary geoheritage

3.1. Quaternary foundations of biodiversity

Quaternary climate change has shaped the distributions of habitats and species over relatively short geological timescales, whilst geomorphological changes modified habitats as glaciers and ice sheets advanced and retreated, and coastlines shifted position. Glacier advances in northern and mid-latitudes isolated plant and animal communities and influenced the locations of refugia. After each glaciation, plant and animal communities re-colonised formerly ice-covered areas. These and other changes are recorded in organic deposits preserved in terrestrial and lacustrine sites. Beyond the Quaternary glacial limits, morphogenetic process zones adjusted to climate shifts, with consequent impacts on habitats and species. For example, changes in monsoon patterns enabled the existence of savannah and diverse wildlife in the Sahara. The Quaternary record therefore provides the context for understanding much of the spatial variation in habitats and biota in the present landscape, which is the focus of nature conservation efforts. For example, the Quaternary record helps to explain the antiquity and

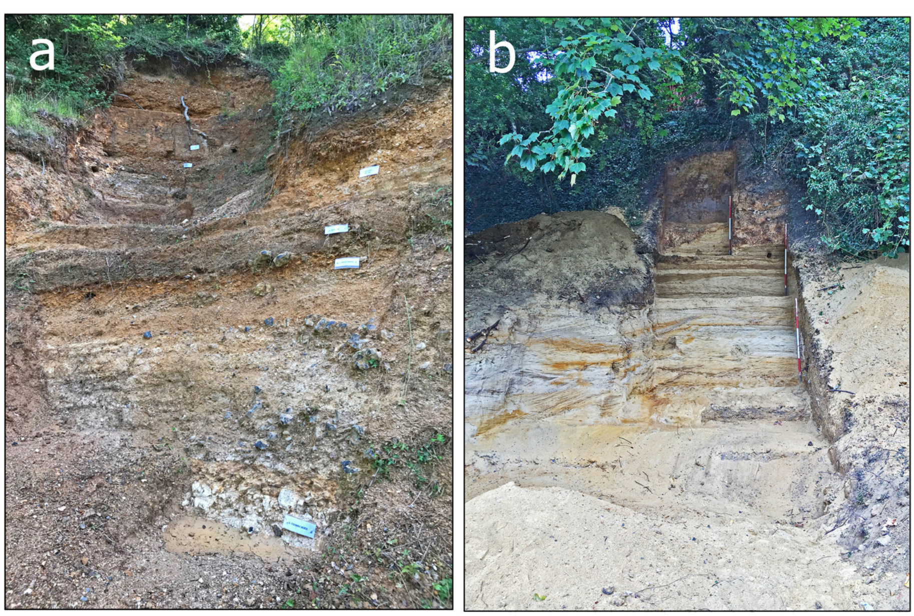

Fig. 2. Examples of site excavations undertaken for scientific meetings. (a) Section in Purfleet Chalk Pits SSSI opened for the INQUA Field Meeting, 'The Quaternary Fluvial Archives of the Major English Rivers', July 2019. The section displays Middle Pleistocene interglacial (MIS 9) sands and gravels associated with a former course of the River Thames. The deposits have yielded animal, mollusc and plant remains, together with evidence of early human occupation. (b) Section in Swanscombe Skull Site SSSI/NNR opened for the European Society of Human Evolution meeting, September 2015. The section in a terrace of the River Thames displays Middle Pleistocene interglacial (MIS 11) sands and gravels which have yielded Palaeolithic artefacts, fragments of a human skull and the remains of mammals and molluscs. Both sites are managed so that temporary sections can be opened when required for research or field meetings. Swanscombe Skull Site SSSI/NNR provides important greenspace for the local community within Swanscombe Heritage Park. Although Purfleet Chalk Pits SSSI has no public access, it is part of an important habitat corridor, providing south-facing bare slopes in soft sediment for invertebrates.
(Images: a Eleanor Brown; b Simon Lewis.)

diversity of biota in the Tibetan region (Spicer et al., 2020) and the history of key species and plant communities during the Holocene, including Scots pine woodland in Ireland (Roche et al., 2018) and Scotland (Edwards et al., 2019). In addition, glaciation and spatial variations in climate during the Quaternary have been suggested as a driver of speciation in diverse environments from alpine to marine areas and a likely influence on resilience to future climate changes (Wallis et al., 2016; Neiva et al., 2018; Trew and Maclean, 2021). In Australia, Fraser Island (K'gari) and the Great Barrier Reef are thought to have formed as a consequence of sea-level fluctuations influencing the coastal sedimentary system during the Middle Pleistocene transition (Ellerton et al., 2022). On a temporal scale, pollen records show that rates of change in vegetation composition during the late Holocene are globally exceptional over the past 18,000 years in their magnitude and extent, exceeding those associated with climatically driven changes at the end of the last glaciation and indicating the scale of impact of human activities on terrestrial ecosystems (Mottl et al., 2021).

Quaternary landforms, sediments and soils not only have their own intrinsic value as part of nature, but also form the foundations of most habitats in terrestrial and marine environments (Kaskela et al., 2017; Lausch et al., 2019, 2020; Lucatelli et al., 2020; Tukiainen et al., 2022). They support habitat diversity as well as providing a platform for specialised habitats such as those associated with limestone pavements and other geomorphological features (Hjort et al., 2015). They also influence the nutrient and water flows that maintain ecosystem functions. Recognition of the fundamental role of these abiotic components has led to the concept of 'conserving nature's stage' as part of a broad-scale approach to assist biodiversity conservation and mitigate biodiversity loss as the climate changes (Anderson and Ferree, 2010; Beier et al., 2015; Gill et al., 2015). This is particularly important in informing biotic responses to climate change where habitat heterogeneity (*i.e.*, geodiversity) is seen as a key factor in enhancing resilience (Willis and Bhagwat, 2009; Willis et al., 2010a; Tscharntke et al., 2012; Anderson et al., 2014, 2015; Theobald et al., 2015). Species and community compositions will change over time, and novel ecosystems likely develop (Hobbs et al., 2009), so that in many cases it will be more effective in the longer term to conserve geodiversity and focus management on conserving ecosystem functions and evolutionary processes than to make futile attempts to preserve the status quo (Pressey et al., 2007; Jackson and Hobbs, 2009; Willis et al., 2010a; Schlaepfer and Lawler, 2022), particularly given uncertainties about rates of migration, *in situ* tolerances, and evolutionary adaptation/phenotypic plasticity in response to past climate changes (Nogués-Bravo et al., 2018). As reflected in numerous studies linking geodiversity and biodiversity (Toivanen et al., 2019; Hu et al., 2020; Salama et al., 2020; Falco et al., 2021), maintaining geodiversity will be essential to enable opportunities for biodiversity in the face of increasing homogenisation of biota (Newbold et al., 2019). A further consideration is that understanding geomorphological responses to climate change and their role in modulating ecosystem disturbance regimes is vital to assist adaptative management in soil, upland, coastal and river environments (Brazier et al., 2012). This needs to consider the interactions between geomorphological and ecological components in biogeomorphological systems, particularly in relation to how these interactions influence the complexities of resistance and resilience (Stallins and Corenblit, 2018). Appreciation of geomorphological processes is also fundamental in providing the physical underpinning for habitat restoration, recovery and nature-based solutions (Cohen-Shacham et al., 2016); for example, in the restoration of rivers and their floodplains (Boon and Raven, 2012; Addy et al., 2016; Brown et al., 2018, 2021), natural flood management (Lane, 2017; Garvey and Paavola, 2022) and adaptation to sea-level rise and coastal erosion (Temmerman et al., 2013; Leo et al., 2019).

3.2. Long-term ecological perspectives

An increasing number of authors have called for better recognition of the value of long-term ecological perspectives for informing nature conservation policy, practice and research priorities. Palaeoecology and palaeobiology have important applications in nature conservation (Willis et al., 2007; Froyd and Willis, 2008; Davies and Bunting, 2010; Seddon et al., 2014; Birks, 2019; Turvey and Saupe, 2019). Used judiciously, they provide the historical context and trends in species composition and ecosystem development, and illuminate the role of climate change and disturbance factors, including human activities, leading to better understanding of ecological and evolutionary processes, climate envelopes and natural variations in species ranges (Willis and Birks, 2006; Froyd and Willis, 2008; Davies and Bunting, 2010; Willis et al., 2010b; Dawson et al., 2011; Vegas-Vilarrubia et al., 2011; Edwards et al., 2019; Trew and Maclean, 2021; Wilson et al., 2021). Notwithstanding that the past may not provide exact analogues for the future, learning from the past can still help to guide conservation strategies to mitigate biodiversity loss. For example, palaeoecological studies can help in evaluating management decisions and interventions for valued habitats (Chambers et al., 1999, 2007; Shumilovskikh et al., 2021), establishing historical species baselines (Grace et al., 2019), informing monitoring and restoration of terrestrial and freshwater ecosystems (Davies and Bunting, 2010; Bennion et al., 2011; Rick and Lockwood, 2013; Foster and Greenwood, 2016), validating ecological models (Anderson et al., 2006), informing reintroductions for conservation, nature recovery and rewilding (Crees and Turvey, 2015; Van Meerbeek et al., 2019; Palli et al., 2022), understanding resilience to disturbance and management of novel ecosystems (Willis et al., 2010b; Buma et al., 2019), appreciating the past ranges of natural variability, past rates and nature of biota responses to climate change, and identifying ecological thresholds and vulnerability to climate change (Gillson and Marchant, 2014; Brown et al., 2020; Trew and Maclean, 2021; Wilson et al., 2021). Palaeoecological studies have also helped to elucidate the role of fire as a disturbance factor, amplifying the effects of climate change and human activities, in the ecological and evolutionary dynamics of terrestrial plant communities (Cole et al., 2022; Lukanina et al., 2022; Napier and Chipman, 2022; Moreno et al., 2023). Impacts from changing fire regimes are predicted to increase in the future because of climate change. From palaeoecological and archaeological evidence and charcoal records, Hawthorne et al. (*this issue*) show that fire has played a part in the evolution of the natural and cultural landscape of Killarney National Park, Ireland, throughout the Holocene, with the role of human influence increasing during the late Holocene. The results provide an extended timescale over which to evaluate fire regimes and vegetation to help inform future fire management planning for the semi-natural native woodland of the National Park and to build ecological resilience (Gillson et al., 2019). Development and application of new analytical techniques emphasise the value of conservation of *in situ* sedimentary records. For example, sedimentary ancient DNA has provided new insights into postglacial plant species arrival and ecosystem changes, showing that ecosystem build-up and establishment of functional diversity and stability in northern Fennoscadia took some millennia (Alsos et al., 2022) and revealed the existence of a unique forested ecosystem in northern Greenland 2 million years ago (Kjær et al., 2022). Palaeoecological studies also have utility in conservation and restoration in that they can provide baseline targets (*e.g.,* more accurate representations of forest composition), as well as indicate the natural range of variability within vegetation composition through time; for example, in demonstrating species compositions and that natural habitats comprised mosaics of open habitat and closed forest in Europe during previous interglacials and before the advent of agriculture and forest clearance by humans during the Holocene (Svenning, 2002).

Long-term studies linking palaeorecords and modelling of future species distributions have the potential to improve conservation assessments as the climate changes (Nogués-Bravo et al., 2016). Palaeoecological records can assist with the inclusion of variability in conservation management and help to determine the range of natural variability (Willis and Birks, 2006), as well as providing data and trends across different temporal scales (Barak et al., 2016; Wingard et al., 2017). They have been used to inform restoration in a range of environments from Scots pine (*Pinus sylvestris*) woodland in Scotland (Davies and Bunting, 2010; Edwards et al., 2019) to the Everglades and the tropics (Vegas-Vilarrubia et al., 2011; Dietl et al., 2015; Rull and Palmer, 2015; Rull et al., 2015; Riedinger-Whitmore, 2016; Castilla-Beltrán et al., 2020) and to peatland conservation and the potential sensitivity of peatland carbon stocks to climate change (McCarroll et al., 2016, 2017; Greiser and Joosten, 2018; Garcin et al., 2022). However, exact analogues from the past are unlikely (Barnosky et al., 2017; Wilson et al., 2021) and restoration to some historical condition, or preservation of the *status quo*, is not likely to be feasible (Hobbs et al., 2009; Davies and Bunting, 2010). Therefore, focusing on conservation of biodiversity *per se* or integrity of ecosystem function and structure or services is likely to be more effective (Barnosky et al., 2017). Novel ecosystems may be anticipated as the climate changes, and priority should be on managing whole landscapes, including novel ecosystems (Hobbs et al., 2014). Consequently, Beller et al. (2020) argued that palaeoecology provides the broader context of human interactions, as well as environmental context, in modifying ecosystems and that both natural and modified ecosystems occur as part of landscape mosaics at different scales and should be managed in that context (Hobbs et al., 2014).

At the broader landscape scale, Delcourt and Delcourt (1988) highlighted the value of Quaternary perspectives to landscape ecology and assessing the role of environmental change, changes in landscape heterogeneity, and human impacts on the landscape. Understanding of changes in slope stability, sediment production, landform distributions, floodplain and wetland histories and flood records can all help to inform landscape-response models and provide pointers for the likely spatial variability, as well as the nature and rate of future catchment responses (Higgitt and Lee, 2001; Lane et al., 2007; Macklin et al., 2010; Chiverrell et al., 2019; Schillereff et al., 2019). In demonstrating that the landscape is a palimpsest, geomorphologically and biologically (Thomas, 2012; Rivera-Núnez and Fargher, 2021), Quaternary studies support landscape-scale approaches to nature conservation. They also illuminate the role of human–environment interactions in shaping the landscape and the effects of human impacts on the environment, thereby helping to discern what is 'natural' or 'semi-natural' from what are culturally derived ecosystems (Whyte, 2006; Grant and Edwards, 2008; Shaw and Whyte, 2013; Shumilovskikh et al., 2021). For example, such studies integrating a range of palaeontological, archaeological and historical data have provided the context for understanding the formation of an 'Anthropocene biota' in the Caribbean (Kemp et al., 2020). Similarly, lake sediment records have provided a wider Holocene perspective on landscape impacts in Iceland, indicating widespread soil erosion before its exacerbation following human settlement (Geirsdóttir et al., 2020). Learning from the past, and particularly from an evolutionary approach rather than use of historical analogues, and from integrated studies of the complex interplay of natural changes (*e.g.*, climate and geomorphological processes), human activities and ecosystem dynamics interacting and evolving together, should provide better understanding of global environmental change at present and in the future and the risks of additive multiple stressors pushing systems towards critical thresholds (Dearing et al., 2010, 2015; van der Leeuw et al., 2011). As ecological restoration and rewilding receive increasing attention, longer-term perspectives gained from Quaternary science are critical to enable consideration of the interactions between human activities and ecosystems under different climatic regimes and hence to better understand landscape evolution and the full extent of human modification of 'natural' landscapes and their associated ecosystems over extended timescales (Boivin et al., 2016; Knudson et al., 2018; Ellis et al., 2021; Thompson et al., 2021; Nogué et al., 2021).

4. Quaternary geoheritage and the developing nature conservation agenda

Reconceptualisation of the values of nature conservation now emphasises the links between nature and people (Mace, 2014). As well as protecting nature, there is a further focus on sustainable management of natural capital, delivery of ecosystem services, developing natural solutions to managing issues such as flooding, sea-level rise and disaster risk reduction, and enhancing health and wellbeing through reconnecting people with nature (Díaz et al., 2015; Pearson, 2016; MacKinnon et al., 2020; Dasgupta, 2021). Many of these issues align with the UN Sustainable Development Goals. The relevance of geodiversity and geoconservation to this wider agenda has been advocated in the geoconservation literature (Gray et al., 2013; Crofts, 2014, 2018; Gordon et al., 2018a, 2018b; Brilha et al., 2018; Gray, 2021; Schrodt et al., 2019; Chakraborty and Gray, 2020). This acknowledges how geodiversity underpins, *inter-alia*, landscape and biodiversity conservation, economic benefits for local communities through geotourism, climate change adaptation, sustainable management of land and water, cultural heritage and people's health and well-being. Therefore, as well as protection of sites for scientific and educational values, the wider intrinsic, cultural, aesthetic and ecological qualities of geodiversity and geoheritage and their contribution to a range of ecosystem services and environmental management are being recognised as a part of geoconservation. These wider values have also been included in resolutions and protected area guidelines produced by IUCN (Dudley, 2008; IUCN, 2008, 2012, 2020; Crofts et al., 2020) and in UNESCO Global Geoparks objectives (UNESCO, 2016, 2017). Nevertheless, the value of geoconservation has received relatively little traction among conservation biologists, policy-makers and the wider nature conservation movement and this remains a key challenge (Brilha et al., 2018; Crofts, 2018). Consequently, there is a vital role for education and outreach at all levels from schools to universities and life-long learning to embed the Quaternary agenda into biodiversity and conservation studies and a more integrated/holistic approach, as well as to improve public understanding of the values of Quaternary geoheritage and the need for its conservation. This should form part of a wider agenda to foster geoscience education and public engagement with geoconservation (*e.g.*, Stewart and Nield, 2013; Crofts et al., 2020; Stewart and Hurth, 2021; Rodrigues et al., 2023).

Conservation of geoheritage sites and landscapes underpins Quaternary science and the benefits it delivers for society. For example, Quaternary landscapes host natural capital that contributes to many of the ecosystem/geosystem services and benefits for society delivered by geodiversity (Gray, 2013; Gordon and Barron, 2013; Gray et al., 2013). These include carbon sequestration, water-quality regulation, natural forms of coastal defence and assets for recreation. From a cultural perspective, as noted above, many Quaternary sites are spectacular landforms that have strong geotourism appeal and aesthetic value and provide sources of inspiration for art, music and literature. The availability and conservation management of key sites and field archives for research and education enable learning from the past to help inform responses to the challenges faced by society today. These include, for example:

- adapting to climate change using information on past climate and environmental changes to facilitate forecasting (*e.g.*, of rates of landscape change, sea-level variations, extreme events and responses of marine and terrestrial ecosystems);
- helping to mitigate natural hazards and informing the management of land and water, including through nature-based solutions (*e.g.*, providing data on historical flooding and droughts; Büntgen et al., 2021);
- mitigating loss of biodiversity;
- identifying early warning indicators of future tipping points and anticipating cascading impacts in the Earth system (Brovkin et al., 2021);
- enhancing the understanding of critical-zone processes: the complex interactions between the atmosphere, hydrosphere, biosphere and lithosphere near the Earth's surface, which regulate and support habitats and life (Anders et al., 2018).

Also, lessons from human responses to past environmental changes can contribute to a better understanding of how resilience and vulnerability occur in human societies through interactions of climate change, socio-economic systems and cultural factors (Hartman et al., 2017; Knudson et al., 2018; Boivin and Crowther, 2021). Quaternary science provides the long-term data that can be applied to understanding climate change and its effects on the natural environment and evaluating climate models (Tierney et al., 2020; Lear et al., 2021). For example, past interglacials with orbital-forcing characteristics similar to those of the Holocene may provide clues about conditions in a future warming world; notable in this respect are the interglacials corresponding with parts of Marine Isotope Stage (MIS) 19 and MIS 11 (Yin and Berger, 2015). Whereas the earlier MIS 19 is difficult to identify unequivocally within the Pleistocene record of Britain and NW Europe, MIS 11 is well represented in the deposits at sites such as Beeches Pit and Clacton (White et al., *this issue*), as well as at the Swanscombe Skull Site SSSI/NNR (see above; Cunha et al., *this issue*; White et al., *this issue*). Quaternary science also informs the restoration of ecosystems, identifies the physical constraints for sustainable development and helps us understand how ecosystem services have changed over time, as well as their resilience and vulnerabilities (Dearing et al., 2012; Jeffers et al., 2015; Pearson et al., 2015).

5. Discussion

Significant progress in Quaternary geoconservation, as in geoconservation more generally, has been achieved over the last few decades, particularly in the UK but also elsewhere. This has taken place through site audits and statutory protection of key sites, development of practical site management (*e.g.*, conservation sections, excavations for field meetings, and collaborations with developers), and advances in the understanding of past environments within the scientific community and the relevance of this understanding to many of the challenges now confronting nature and society. Although the case studies in this Special Issue and the research literature examined in this paper recognise the nature conservation value of Quaternary science, this is not yet translated effectively into nature conservation practice in terms of planning future site conservation networks and effective site management strategies in the face of climate change, both in terrestrial and marine environments. Similarly, despite advocacy from the geoconservation community, geodiversity and geoheritage more generally still need to be integrated into assessments of critical natural assets, studies of the connections between nature and people and implementation of nature-based solutions (*cf.*, Díaz et al., 2018; Chaplin-Kramer et al., 2022). Integrated studies are also needed to help strengthen landscape-scale conservation measures that recognise the links between geodiversity, biodiversity and cultural influences.

In looking ahead, two priority challenges for Quaternary geoheritage and nature conservation emerge from the papers in this Special Issue and from this review, but also apply more widely across other areas of geoheritage:

1. to maintain up-to-date geoconservation audits and ensure effective conservation for networks of key geoheritage sites and archives; and
2. to achieve better integration of geodiversity/geoheritage, biodiversity and cultural interests at research, policy and practical levels, to help deliver multiple benefits for nature and people as set out in IUCN Resolutions.

As identified in the papers in this Special Issue by Dempster and Enlander, Tisdall and Miller, Dale et al., Hazell et al. and Cunha et al., both of these challenges require the Quaternary geoconservation and geoscience communities to look outwards and to engage with stakeholders. Specifically, this needs to be achieved by targeting decision- and policy-makers and their advisors, planners, land and water managers, and the wider nature conservation community, making sure the results of geoconservation audits are addressed in the planning system, expanding heritage designations to include Quaternary landscapes, and including palaeoecology more widely in nature conservation designations. This will enable geoconservation to become mainstreamed in environmental strategies, policies and practices at all scales from the local to the global (Prosser et al., 2013; Gordon et al., 2018b). There is also an urgent need for enhanced public outreach to promote better awareness of the values and benefits of Quaternary science and geoheritage. As identified in the papers by Dale et al., Hazell et al., Cunha et al., Hawthorne et al. and Aytac et al., solutions will require multidisciplinary research, using Quaternary science to inform management, reviewing lessons learned, overcoming the nature/culture divide and taking an integrated approach in protected areas and at a landscape scale. Practical demonstration, including case studies, will be essential to illustrate the benefits of collaborative working and eliminating barriers to communication and knowledge exchange across disciplines, spanning geodiversity, biodiversity and cultural heritage (Knudson et al., 2018) and between ecology and palaeoecology (Birks, 2012; Bjune et al., 2015; Nieto-Lugilde et al., 2021). Better communication will also be required between scientists, policy-makers and those working in practical nature conservation, with research presented in a form that is relevant, evidence-led and focused on priorities, and that contains real-world examples of practical steps and solutions (Alahuhta et al., 2022; Gordon et al., 2022; Tukiainen and Bailey, 2022).

In addressing these challenges as part of forward-looking nature conservation, dynamic and adaptive approaches will be needed rather than attempts to preserve the status quo (Young and Duchicela, 2021; Schlaepfer and Lawler, 2022; McGuire et al., 2023). These approaches should be informed by learning lessons from the past as recorded in Quaternary archives, including appreciation that change is normal albeit compounded increasingly by anthropogenic activities. Crucially, therefore, as well as conservation of sites for their intrinsic geoheritage value, it will be vital "to select and conserve sites that will satisfy future demands for information about the past, without knowing the questions to be addressed nor the methodologies that will be available" (Greiser and Joosten, 2018, p. 209).

6. Conclusions

Quaternary sites and features merit conservation in their own right as part of geoheritage and also for their wider values as part of nature and natural heritage. The INQUA session examined the importance of conserving and managing our Quaternary geoheritage and the application of Quaternary science to current nature conservation issues. Conserving Quaternary geoheritage celebrates the history of science, conserves scientifically valuable field sites and *ex situ* resources for research and education, supports landscape and biodiversity conservation and fosters sustainable economic development through geotourism activities. It also helps to inform climate change adaptation, sustainable management of land and water, and maintains important components of natural capital and ecosystem services, including supporting historical, cultural and geoarchaeological heritage, and people's health and well-being. From a biodiversity viewpoint, an understanding of ecological and evolutionary processes, long-term ecosystem dynamics and past ranges of natural variability from Quaternary science should lead to better informed conservation management strategies and practice.

Fresh approaches are required that integrate geoconservation and better understanding of Quaternary science and geodiversity in nature conservation research, policy development and practice. This applies not only to mitigation of biodiversity loss and adaptation to climate change through nature-based solutions, but also to broader issues of sustainable environmental management that recognise the connections between nature and people. In turn, fully integrating Quaternary science and geodiversity should benefit not only geoheritage, but also more holistic approaches to nature conservation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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