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Geoconservation principles and protected area management

John E. Gordon

School of Geography & Sustainable Development, University of St Andrews, St Andrews KY16 9AL, Scotland, UK

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Geoconservation includes the protection of geoheritage features and geosites and the application of geoconservation principles more generally in the sustainable management of protected areas and in the wider landscape. This article reviews: 1) geoconservation principles and objectives for geosite management planning; and 2) the wider relevance of geoconservation and how the application of geoconservation principles across the full range of IUCN protected area management categories, UNESCO Global Geoparks and Biosphere Reserves, World Heritage sites, Ramsar sites and marine protected areas would benefit conservation of biodiversity and geodiversity and support wider nature conservation objectives, including climate change adaptation, connecting people and nature and sustainable development. In particular, the concepts of 'nature and people' and 'conserving nature's stage' provide opportunities for developing more holistic approaches to nature conservation.

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E-mail address: jeg4@st-andrews.ac.uk.

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1. Introduction

Geoconservation involves the protection of those elements of geodiversity that have geoheritage value principally for scientific reasons, but also for supporting educational, cultural, aesthetic, spiritual and ecological values (Crofts & Gordon, 2015; Gray, 2013).While there has been significant progress in the identification of terrestrial geosites, especially in Europe (Wimbledon & Smith-Meyer, 2012), there has been less emphasis on practical site management and the application of best-practice based on sound geoconservation principles. This is now a priority in the face of a wide range of threats to geoheritage, including urbanisation, infrastructure development, mineral extraction, changes in land use and coastal protection (Crofts & Gordon, 2015).

Some authors restrict geoconservation to the protection and management of geoheritage; others allow a broader interpretation that includes conservation of geodiversity where that has demonstrated value (e.g. to ensure the functioning of healthy ecosystems and the services they provide), but not conservation of all geodiversity regardless of its value since that is clearly impossible. While the protection of geosites remains the foundation of geoconservation, a broader discipline has been emerging (Brilha, Gray, Pereira, & Pereira, 2018; Gray, 2013; Henriques, Pena dos Reis, Brilha, & Mota, 2011). This recognises the links of geodiversity with landscape and biodiversity conservation, economic development, climate change adaptation, sustainable management of land and water, historical and cultural heritage, people's health and well-being, geotourism and the delivery of socio-economic benefits for local communities (Prosser, Bridgland, Brown, & Larwood, 2011; Prosser, Brown, Larwood, & Bridgland, 2013; Gordon, Barron, Hansom, & Thomas, 2012; Gordon, Crofts, Díaz-Martínez, & Woo, 2018; Gray, 2013). Therefore as well as scientific value, growing emphasis is now placed on the wider intrinsic, cultural, aesthetic and ecological qualities of geodiversity and geoheritage and their contributions to a range of ecosystem services (Brilha et al., 2018; Gordon & Barron, 2013; Gray, 2012; Gray, Gordon, & Brown, 2013). This is acknowledged in the International Union for Conservation of Nature (IUCN) Resolutions 4.040 (IUCN, 2008) and 5.048 (IUCN, 2012), which state that geodiversity is part of nature and that geoheritage is part of natural heritage. Both resolutions also highlight the wider role of geodiversity in underpinning biological, cultural and landscape diversity. Further recognition of geodiversity within IUCN is reflected in the establishment in 2014 of the Geoheritage Specialist Group within the World Commission on Protected Areas (https://www.iucn.org/commissions/world-commission-protected-areas/our-work/geoheritage), in the inclusion of a chapter on geoconservation in IUCN's *Protected Area Governance and Management* e-book (Crofts & Gordon, 2015) and in the preparation of *Guidelines on Geoconservation in Protected Areas* in the IUCN Best Practice Protected Area Guidelines Series (Crofts, Gordon, Gray, Tormey, & Worboys, forthcoming).

Geodiversity was formally recognised as a component of protected areas in the revised *IUCN Guidelines for Applying Protected Area Management Categories* (Dudley, 2008). This means that geoconservation can form part of the rationales and management objectives for all 6 protected area categories (strict nature reserve/wilderness area, national park, natural monument or feature, habitat/species management area, protected landscape/seascape, and protected area with sustainable use of natural resources) and should not be restricted to Category III (Natural monument or feature) (Crofts & Gordon, 2015). Sites or features of geoheritage value may occur within a wide range of protected area categories either as the primary conservation interests or often as part of a wider range of natural or cultural interests. Geodiversity and geoheritage are also incorporated in the list of criteria for the World Heritage List, specifically under criterion (viii) and implicitly as supporting elements of other natural and cultural criteria. In addition, geodiversity and geoheritage interests may form supporting components of UNESCO Biosphere Reserves and Ramsar sites, and their presence is a fundamental requirement for UNESCO Global Geoparks. Although largely neglected, geoconservation is similarly relevant in the marine environment, both for the geoheritage values of specific features and for the role of geodiversity in supporting biodiversity in marine protected areas and in informing marine spatial planning (Buhl-Mortensen, Buhl-Mortensen, Dolan, & Gonzalez-Mirelis, 2015; Burek, Ellis, Evans, Hart, & Larwood, 2012; Fischer, Bhakta, Macmillan-Lawler, & Harris, 2019; Gordon et al., 2016; Harris & Baker, 2020). Hence the presence and values of geoheritage and geodiversity should be identified and recognised in the management of all categories of terrestrial and marine protected areas, including those where the objectives are primarily the conservation of biodiversity or cultural heritage. As discussed below, such an integrated approach can have benefits for all of nature and people.

Nevertheless, the values of geodiversity and geoheritage are still poorly incorporated in protected area management. There are several reasons for this, including poor communication and lack of awareness of the value of integrating geodiversity in ecosystem management and delivering sustainable development (Brilha et al., 2018; Crofts, 2014; Gray et al., 2013). Drawing on the work of the IUCN Geoheritage Specialist Group and the IUCN *Guidelines on Geoconservation in Protected Areas* (Crofts et al., forthcoming; Crofts & Gordon, 2015; Gordon, Crofts, Díaz-Martínez, & Woo, 2018), this article reviews geoconservation principles and practice: first, in relation to the management of geosites; and second, in protected area management more generally.

2. Conservation of geoheritage in protected areas: principles and practice of site management planning

The principal steps in the development of an effective geoconservation strategy for an area or a country involve: 1) inventory of geoheritage interests and sites; 2) assessment of their values; 3) conservation management; 4) monitoring; and, where appropriate, 5) promotion through interpretation (Brilha, 2016). Site inventory and assessment methodologies across a range of scales from local to national are widely described in the literature (e.g. Brilha, 2018; Garcia, Brilha, Lima, et al., 2018) and are not discussed here. The remaining steps form part of site management planning. A management plan provides a structured approach for the management of a protected area. It establishes the legal basis for protection; the tenure status of land; the authority responsible for management; the vision for the protected area, including its purpose (proposed use) and the targets for its favourable condition; and the objectives of management and the actions necessary to achieve those objectives (Spoelder, Lockwood, Cowell, Gregerson, & Henchman, 2015). Site management planning essentially involves two stages: 1) a conservation needs analysis which requires assessment of a site's use, character, threats and sensitivity; and 2) conservation planning and delivery (Prosser, Díaz-Martínez, & Larwood, 2018). As exemplified by Wimbledon, Barnard, & Peterken (2004), these two stages involve six requirements to be addressed in incorporating geoconservation into the preparation of comprehensive site management plans: 1) documentation of key interests; 2) specification of management objectives and targets; 3) assessment of risk and vulnerability to pressures and threats; 4) management zoning and identification of core and buffer zones; 5) site condition monitoring; and 6) periodic plan review. IUCN's *Guidelines on Geoconservation in Protected Areas* reviews these stages and provides protected area managers and staff, and their advisors, with practical information and guidance (Crofts et al., forthcoming).

2.1. Documentation of key interests

Documentation of key interests is normally carried out by specialists and may include field survey and mapping, use of annotated photography and with outputs presented in a form that is accessible to non-specialist landowners, protected area managers and rangers. Site documentation also provides a baseline for site condition monitoring.

2.2. Specification of management objectives and targets

Development of management objectives includes: evaluation of actual and potential uses (e.g. for science, education, geotourism); identification of opportunities for interpretation, promotion and geotourism; and setting site condition targets. Management objectives should reflect the vision and purpose of the site, the different types of geoheritage interest present and the potential values and uses of the site. Protection of geoheritage interests will normally be the primary management objective. Complementary objectives may recognise the wider instrumental and relational values of geoheritage (e.g. cultural and aesthetic values, value for geotourism and conservation of biodiversity and other ecosystem service values) where they do not conflict with geoheritage protection.

Management objectives should be tailored appropriately for different types of interest and categories of geoconservation site, recognising their different requirements. For example, in Great Britain, generic objectives are based on a tripartite classification of sites, which may occur as natural and man-made exposures, landforms or active geomorphological systems (Prosser et al., 2018; Prosser, Murphy, & Larwood, 2006). Where there is a substantial reserve of rock or sediment, and the interest is not localised, the main conservation principle is that removal of material does not necessarily damage the resource as new exposures of the same type will be freshly exposed (Fig. 1A). Sites where the interest is localised or finite (e.g. geological type sites, occurrences of Quaternary interglacial deposits or fossil-bearing horizons) (Fig. 1B) require careful management to protect the resource from depletion or loss of material. Geomorphological sites include both static (inactive) features (e.g. Pleistocene glacial landforms) and active features (e.g. coastal and river landforms), and damage to one part of a site is likely to be detrimental to the value of

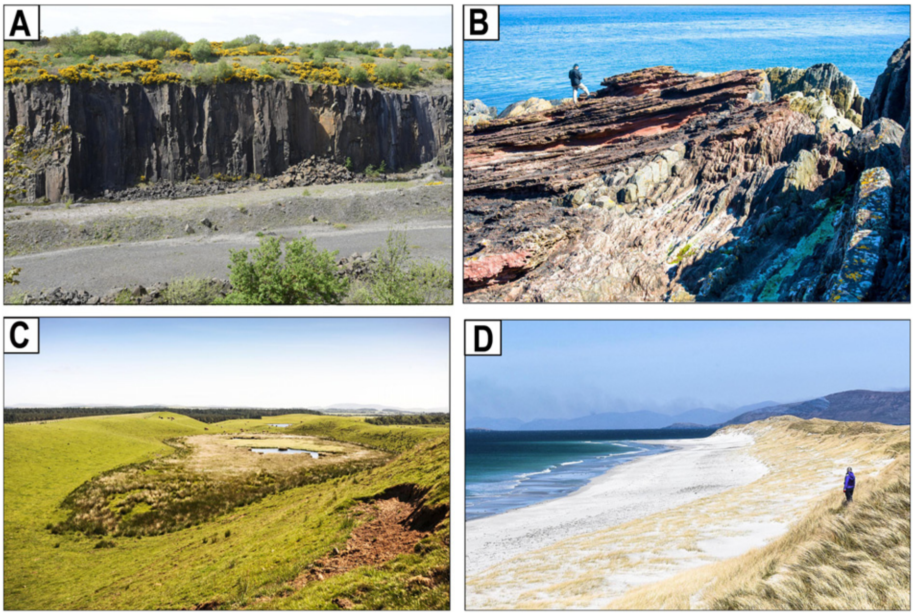

Fig. 1. A. Extensive exposures of a Permo-Carboniferous quartz-dolerite sill in a disused quarry. B. Siccar Point, Scotland, is a unique exposure of very limited extent, where James Hutton in 1788 demonstrated an immense gap in geological time represented by the unconformity between the steeply dipping Silurian greywacke sandstones and the overlying and gently dipping Devonian red sandstones. C. Esker landforms formed by Pleistocene glacial meltwaters. These ridges of sand and gravel are relict features and are vulnerable to damage and destruction from mineral extraction. D. Coastal beach and sand dune system evolving naturally through active movement and interchange of sand between the nearshore, foreshore, beach and dune areas.

the whole site (Fig. 1C, D). The main management principle for static features is to protect their integrity. If damaged or destroyed, they cannot be reinstated or replaced since the processes that formed them are no longer active. For active geomorphological sites, the key principle is to allow the active processes and landforms to evolve naturally. Where intervention is essential, 'soft' solutions that have a minimal impact on the protected area features are recommended (e.g. Scottish Natural Heritage, 2000; River Restoration Centre, 2013). Active geomorphological sites may also be susceptible to changes outside the protected area boundary (e.g. through upstream changes that affect river discharge and sediment throughputs downstream).

As well as the physical characteristics of a site, there are a number of other factors to be considered in setting management objectives. The appropriateness of existing or proposed activities should be considered. For example, not all sites are suitable for geotourism. Does a site have features that are suitable for education and interpretation that are both engaging and interactive for different audiences, or is the interest too specialised for the general visitor? Some sites may present significant hazards or safety issues for visitors, which cannot easily be managed or mitigated (Brocx & Semeniuk, 2019). Others may be vulnerable to trampling which will damage fragile forms, necessitating specific visitor management measures, zoning or installation of boardwalks. Sites with rare fossils and minerals will need protection from commercial collectors and irresponsible fossil collecting. Specific guidelines and codes of conduct have been produced in Great Britain to address the latter issues. For example, the Scottish Geodiversity Forum (2015) has developed an Ethical Rock Collecting Policy, and the Scottish Fossil Code (Scottish Natural Heritage, 2008) encourages responsible collecting and sets out best practice and guidance for the collection and care of fossil specimens. Some sensitive sites with rare or fragile interests may require managed access through permit systems or through accompanied visits. In some cases, maintenance of traditional access where there are local cultural and/or spiritual interests may need to be considered.

A site management plan should also set out targets for the site to be in favourable condition and the decision triggers for management interventions. For example, a management objective may be to maintain the site in favourable condition so that the physical attributes (extent, structure and composition of the features) are intact, clearly visible and accessible for the purposes of research and education, and to encourage responsible visitor access to the site for the purposes of recreation and geotourism. A specific target for favourable condition could be to require at least 75% of the site to have clean and accessible exposures of a particular rock sequence and its key features (see Wimbledon et al., 2004). Where the site condition falls below, say, 50% of clearly visible exposures, then vegetation clearance or talus removal may be triggered. The targets will depend on the particular types of use and frequency of use of the site. A site that has a high frequency of use (e.g. for education or geotourism) may require regular maintenance, whereas one that is used infrequently for research may require only occasional interventions.

2.3. Assessment of risk and vulnerability to pressures and threats

Geosites are vulnerable to a wide range of pressures and threats from human activity, including urbanisation; commercial, industrial and infrastructure developments; mineral extraction; land use changes; coastal defences; river engineering for flood and fisheries management; and loss of moveable geoheritage (e.g. fossil and mineral specimens) (Crofts et al., forthcoming). Vulnerability is the degree to which a site or system is susceptible to, and unable to cope with, adverse effects. This depends on the system's sensitivity and ability to adapt. Sensitivity is the degree to which a system is affected or will respond. The evaluation of the sensitivity of rock exposures and relict landforms is relatively straightforward, based on a simple assessment of the likely scale of impact and loss of interest (Sharples, 2002). For active geomorphological systems, additional factors are the resilience of the system and its potential dynamic response, including possible prolonged readjustment (that may or may not lead to recovery) or change in state (for example, from a braided to a meandering river) (Kirkbride & Gordon, 2010). Assessment of risk is based on risk-rating matrices and evaluation of likelihood of detrimental impact of the activity and the predicted severity of impact. Essentially this comes down to a value judgement informed by site type, vulnerability and sensitivity.

2.4. Management zoning and identification of core and buffer zones

Core areas are defined to ensure secure protection of the geoheritage interest. Buffer areas provide context and may be used for a wider range of activities compatible with sound geoconservation principles and practice, including environmental education, recreation and geotourism. The extent of buffer areas will depend on the nature and scale of the interest. For example, a small rock exposure may have a relatively small buffer area, whereas a glacial landform may form part of a more extensive landform assemblage. In the case of active process systems such as caves, the whole drainage catchment area may form part of the buffer zone for the cave passages.

2.5. Site condition monitoring

The purpose of site condition monitoring is to establish whether conservation objectives and targets are being met. Protocols for monitoring need to be set, including a baseline, the key attributes to be assessed against the targets and the frequency of monitoring. Attributes will generally include the integrity of the physical attributes of the site (extent, structure and composition of the features), their visibility and access, and the integrity of geomorphological processes where these form part of the interest (e.g. Wignall, 2019). The frequency of monitoring is determined by the degradation potential of the site and the risk assessment. If required, remedial action may be triggered as part of the management review process.

2.6. Periodic plan review

Periodic review and evaluation of site management plans and their performance is an essential part of the planning process. The frequency will depend on a number of factors, including the sensitivity of the site, risk of known threats and the results of site condition monitoring.

2.7. Overview

These principles apply to the conservation of geoheritage not only within geosites, but also within the full range of categories of protected area, including those where geoheritage is not the primary reason for protection. For all categories of protected area, geoheritage considerations should be an integral part of the protected area management plan.

3. Integrating geoconservation in wider protected area management

The integration of geoconservation across the full range of IUCN protected area management categories, as well as UNESCO Global Geoparks and Biosphere Reserves, World Heritage sites, Ramsar sites and marine protected areas should help to enhance their management and to deliver more effective nature conservation, with consequent benefits for geoheritage, biodiversity and people. This requires: 1) a rigorous and systematic approach to all aspects of geoheritage site identification, assessment, management and monitoring within existing protected areas, as outlined above and in the IUCN *Guidelines on Geoconservation in Protected Areas* (Crofts et al., forthcoming); and 2) the recognition of the wider values of geoconservation outwith specific geosites and the application of some basic geoconservation principles (Table 1). While these principles may be self-evident within the geoconservation community, they have been largely overlooked in biodiversity-focused approaches to nature conservation and the historical separation of biodiversity from geodiversity in protected area management (Crofts, 2014), this despite the multiple links and feedbacks between geodiversity and biodiversity (Corenblit et al., 2011; Reinhardt, Jerolmack, Cardinale, Vanacker, & Wright, 2010). Similarly, in Western thinking, nature has been viewed as something apart from people. However, two recent paradigm shifts in nature conservation, have emphasised the concepts of 'nature and people' and 'conserving nature's stage'. Essentially the two concepts are complementary (Knudson, Kay, & Fisher, 2018) and provide opportunities for developing more integrated approaches linking geodiversity, biodiversity and people (Brilha et al., 2018; Gray, 2018; Peña, Monge-Ganuzas, Onaindia, Fernández de Manuel, & Mendia, 2017; Schrodt, Bailey, Kissling, et al., 2019).

3.1. Nature and people

Recognition of the value of nature for people has been expressed in the concept of ecosystem services (Millennium Ecosystem Assessment, 2005), which highlights the role of regulating, supporting, provisioning and cultural services provided by nature and natural resources (natural capital). More recently, in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), this has been developed in the concept of 'nature's contributions to people', and although it incorporates the mediating role of culture in the links between people and nature (Díaz, Pascual, Stenseke, et al., 2018), the emphasis is on nature for people rather than on a more symbiotic relationship between nature and people (Mace, 2014). Paradoxically, IPBES also excludes

Table 1
Geoconservation principles and guidance for protected area management (adapted from Crofts & Gordon, 2015; Gordon, Crofts, Díaz-Martínez, & Woo, 2018).

Geoconservation principle	Protected area management guidance
Effective geoconservation requires a systematic approach to all aspects of site identification and management.	Follow the advice in the IUCN *Best Practice Guidelines on Geoconservation* to identify, protect and interpret geoheritage within all protected areas.
Geodiversity and geoheritage have intrinsic, scientific, educational, aesthetic, spiritual, cultural and ecological values.	Integrate the multiple values of geodiversity and geoheritage in protected area management and interpretation, recognising their contributions to natural capital and ecosystem services, connecting people and nature, and developing natural solutions to global challenges and the UN Sustainable Development Goals.
Multiple connections, interactions and feedbacks exist between geodiversity, biodiversity and people.	Adopt a holistic approach in protected area design and management, integrating geo, bio and cultural interests.
Manage natural systems by 'working with nature'.	This requires: • Recognising the value of geodiversity and 'conserving nature's stage'; • Recognising the inevitability of natural change and planning for such change; • Making space to enable natural processes to operate over the full range of their natural variability; • Managing natural systems in a spatially integrated manner and maintaining the connectivity of natural processes and landform elements; • Recognising the sensitivity of geosites and natural systems and managing them within the limits of their capacity to absorb change where pressures and threats can be controlled (e.g. through visitor management); • Learning from the past and applying understanding of physical processes and landscape evolution.

the contributions of non-living nature (i.e. geodiversity) to people. In a more holistic approach, managing protected areas should not only protect all of nature for its inherent value, including both biodiversity and geodiversity interests, but also sustain natural capital, deliver ecosystem services and help in the development of natural solutions to existing and emerging global challenges, such as climate change, disaster risk reduction, food and water security, enhancing spiritual, physical and mental health, and reconnecting people with nature (MacKinnon & Londoño, 2016; Pearson, 2016).

As noted in the introduction, there are growing calls from the geoconservation community that inclusion of geodiversity and geoconservation is vital in addressing these issues. This is now being addressed in strategic approaches to geoconservation at an international level, as recognised in IUCN Resolutions 4.040 and 5.048 and in the development of UNESCO Global Geoparks. In particular, the contributions of geodiversity and geoconservation to the UN Sustainable Development Goals, ecosystem services, natural capital and climate change adaptation offer significant opportunities to mainstream geoconservation in the wider nature conservation agenda (Everard & Quinn, 2015; Gill, 2017; Brilha et al., 2018; Gordon, Crofts, Díaz-Martínez, & Woo, 2018; Gordon, Crofts, & Díaz-Martínez, 2018). This is clearly demonstrated in a growing number of case studies where geodiversity understanding and data are seen as essential to address these complex issues (Table 2) and to help support appropriate policies that follow a more holistic approach (Schrodt et al., 2019; Stewart & Gill, 2017). However, this is not without its challenges, and while there are strong arguments for more holistic approaches, institutional and other barriers remain to be overcome (Brilha et al., 2018; Gray, 2018).

3.2. Conserving nature's stage

3.2.1. Recognising the interactions and interdependencies of geodiversity and biodiversity to enhance protected area planning

The characteristics of the substrate geology, landforms, soils and geomorphological, hydrological and biogeochemical processes, interacting with climate, provide the foundation for biodiversity, or 'nature's stage' (Anderson & Ferree, 2010; Beier, Hunter, & Anderson, 2015). For example at global and regional scales, present-day centres of species richness are linked with mountain areas with high rainfall, temperatures and diverse topographic relief (Antonelli et al., 2018; Barthlott, Mutke, Rafiqpoor, Kier, & Kreft, 2005; Zarnetske et al., 2019). At a finer scale, the distributions of plant species and communities are closely associated with soils and geomorphological processes in conjunction with micro-topographical and micro-climatic conditions (Jačková &

Table 2
Wider relevance of geodiversity to informing current conservation issues and drivers.

Conservation issues and drivers	Examples of the contribution of geodiversity understanding and data	Selected references
Reversing biodiversity loss and delivery of the Convention on Biological Diversity Aichi targets (e.g. Targets 11, 14 and 15)	Conserving nature's stage - the physical features and natural processes that support biodiversity	Anderson & Ferree, 2010; Beier & Brost, 2010; Anderson, Clark, & Sheldon, 2014; Anderson et al., 2015; Lawler et al., 2015
Climate change adaptation	Understanding how geomorphological sensitivity to climate change will influence biodiversity adaptations; conserving nature's stage and informing natural solutions; providing environmental heterogeneity, macro- and micro-refugia, landscape and process connectivity	Orford & Pethick, 2006; Dobrowski, 2011; Brazier, Bruneau, Gordon, & Rennie, 2012; Anderson et al., 2014, 2015; Opedal, Armbruster, & Graae, 2015; Theobald, Harrison-Atlas, Monahan, & Albano, 2015
The ecosystem approach and landscape-scale conservation	Conserving nature's stage and understanding the role of physical processes and the links between geodiversity, biodiversity and people across different spatial scales	Thorp et al., 2010; Semeniuk, Semeniuk, Tauss, Unno, & Brocx, 2011; Hjort, Heikkinen, & Luoto, 2012; O'Callaghan, Hannah, Williams, & Sadler, 2013; le Roux & Luoto, 2014; Gray et al., 2013; Zarnetske et al., 2019;
Natural capital and ecosystem services	Providing many valued ecosystem services; enable understanding of ecosystem history and long-term trends in ecosystem services represented in palaeoenvironmental records	Gordon & Barron, 2013; Jeffers, Nogué, & Willis, 2015; Van der Meulen, Braat, & Brils, 2016; Van Ree & van Beukering, 2016; Gray, 2012, 2018; Alahuhta et al., 2018; Garcia, 2019
Marine conservation	Supporting biodiversity in marine protected areas and informing marine spatial planning and coastline management based on understanding of physical processes	Buhl-Mortensen et al., 2015; Finnegan et al., 2015; Durán Vinent & Moore, 2015; Kaskela et al., 2017
Soil conservation	Understanding the role of physical processes, particularly in relation to habitat support, soil erosion and carbon management	Thwaites, 2000; Ibáñez & Bockheim, 2013; Ibáñez, Zuccarello, Ganis, & Feoli, 2014
Links between people, place and nature	Understanding the many influences of geodiversity on cultural heritage and how they help to enhance local communities' sense of place and in developing sustainable activities such as geotourism	Knight & Harrison, 2013b; Gordon, 2018; Reynard & Giusti, 2018
Habitat restoration and management	Informing restoration strategies through understanding of, and working with, natural processes; understanding of ecosystem history from palaeoecological records	Newson & Large, 2006; Beechie et al., 2010; Nordstrom et al., 2011; Jackson, Nordstrom, Feagin, & Smith, 2012; Gillson, Dawson, Jack, & McGeoch, 2013
Delivering the UN Sustainable Development Goals	Informing nature-based solutions to global environmental challenges, human well-being and ecosystem functioning	Stewart & Gill, 2017; Schrodt et al., 2019

Romportl, 2008; Knight, Grab, & Carbutt, 2018; Opedal et al., 2015; Tukiainen, Bailey, Field, Kangas, & Hjort, 2017). Over long time scales, geological processes have influenced the evolution and distribution of biodiversity at global and regional scales (Gill et al., 2015; Hoorn et al., 2010), as seen, for example, in the role of glaciation as a driver of mountain speciation (Wallis, Waters, Upton, & Craw, 2016). Complex geology, soil and landform mosaics, and geomorphological processes and disturbance regimes enhance environmental heterogeneity (Fig. 2A) (le Roux & Luoto, 2014; le Roux, Virtanen, & Luoto, 2013; Tukiainen et al., 2017; Tukiainen, Kiuttu, Kalliola, Alahuhta, & Hjort, 2019). Such areas of high geodiversity tend to support high biodiversity and species richness, enhancing the availability of niche space, refuges and opportunities for species diversification (Stein, Gerstner, & Kreft, 2014). In other cases, rare or unique biota are adapted to particular abiotic conditions (Fig. 2B) (Hjort, Gordon, Gray, & Hunter, 2015). Hence, maintenance of geodiversity and the application of geoconservation principles in wider protected area management should enhance conservation of biodiversity. This is supported by a growing number of studies across a range of terrestrial, freshwater and marine environments, which emphasise the importance of understanding the interactions between geodiversity and biodiversity as a basis for improved conservation planning and management (Herkül, Aps, Lokko, Peterson, & Tõnisson, 2018; Kärnä et al., 2019; Kaskela et al., 2017; Toivanen et al., 2019; Tukiainen et al., 2019; Yizhaq, Stavi, Shachak, & Bel, 2017). Hence 'conserving nature's stage', by focusing on areas of high geodiversity that have the potential to support high biodiversity under future environmental changes, as well as small natural features with large ecological roles (Hjort et al., 2015; Hunter et al., 2017), is advocated as a coarse filter approach for conserving biodiversity (Lawler et al., 2015). While species and communities may change, conserving geodiversity and making space for natural processes that enhance landscape heterogeneity enhances opportunities for biodiversity to adapt or relocate under both current and future climates. Conserving nature's stage is central to recent guidance that highlights the value of environmental heterogeneity in building climate resilience and adaptive capacity since geodiverse, heterogeneous landscapes support high biodiversity and provide future habitat space, evolutionary potential, refugia and connectivity corridors (Gross, Woodley, Welling, & Watson, 2016; Knudson et al., 2018; Schmitz et al., 2015; Theobald et al., 2015). Protected area planning that incorporates geodiversity as well as biodiversity should therefore enhance resilience and adaptive capacity, sustain key abiotic processes and result in a system of protected areas that is more representative of a region's natural diversity (Anderson et al., 2015; Lawler et al., 2015).

3.2.2. Planning for change

Protected area design has conventionally been based on the assumption of relatively static conservation interests (Hagerman, Dowlatabadi, Chan, & Satterfield, 2010; Pressey, Cabeza, Watts, Cowling, & Wilson, 2007). However, in the face of climate change, a shift in focus is required from short-term preservation to planning for such change and its effects in the medium to longer term. Apart from robust rock features, this applies equally to geoheritage interests (Prosser et al., 2010; Sharples, 2011). Conserving nature's stage can be viewed at a range of spatial and temporal scales, although attention has been on meso-scales (>100 km^2) which are viewed as relatively static with stable geology, soils and topography over centennial to millennial timescales (Theobald et al., 2015). However, from a geomorphological perspective, in many environments the stage is not static. In a

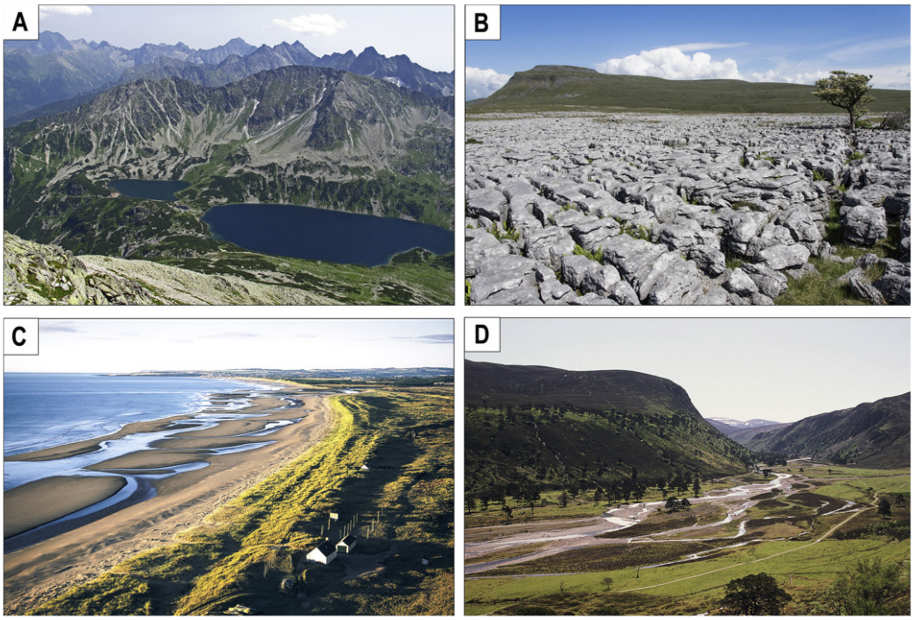

Fig. 2. A. Geomorphologically dynamic environments of the Tatra Mountains Biosphere Reserve and National Park, Poland/Slovakia, provide a mosaic of alpine and sub-alpine habitats that support rare endemic and relic species. B. The cracks in glacially scoured limestone pavement in northern England provide moist and sheltered habitats for specialised plants, insects and snails. C. Climate change and sea-level rise will lead to geomorphologically more dynamic coastal landscapes, presenting challenges for protected area management as shorelines move landwards. D. Maintaining natural flow regimes and river channel-floodplain connectivity provides mosaics of habitats, enhances geodiversity and biodiversity, and supports natural flood mitigation.

dynamic world, the response of geomorphological processes to climate change will have significant impacts on ecosystems and influence biodiversity adaptations to climate change over a range of timescales (Fig. 2C) (Brazier et al., 2012). There will be impacts on the condition of habitats and species from:

- increased rates, occurrence and intensity of flooding, slope failure, erosion, sediment supply and transfer, river channel mobility and coastal change;
- changes in the spatial distributions of landforms (e.g. saltmarshes and sand dune systems as coastlines migrate landwards and patterns of erosion and deposition alter);
- increased frequencies and rates of geomorphological change that are too fast for some habitats and species to adapt or relocate naturally;
- less recovery time between extreme events (e.g. wash-out of spawning areas), so that habitat and species recovery are never fully established;
- reduced habitat availability from coastal retreat, squeeze and steepening and as morphogenetic zones move up mountain slopes;
- changes in seasonal processes (e.g. the timing and duration of droughts);
- geomorphological responses in one part of a river catchment or coastal cell affecting downstream habitats and species (e.g. arising from changes in discharge or sediment transfer).

In addition, management responses to flooding and sea-level rise (e.g. demands for more coast protection) may have significant knock-on effects (e.g. reduced sediment supply to maintain beaches and dunes).

Some geomorphological systems will be more resilient than others. However, some geomorphological changes are likely to be non-linear, and if limiting thresholds are crossed, the original features and processes may be irreversibly changed (Durán Vinent & Moore, 2015). Nevertheless, the impacts of geomorphological change will not necessarily be adverse for biodiversity, since the disturbance regimes may enhance environmental heterogeneity and provide new opportunities for biodiversity. Planning for change requires understanding of geomorphological sensitivity, managing natural systems within the limits of their capacity to absorb change, insofar as that is known, and preferably adopting a precautionary approach where local stresses can be managed (e.g. land use pressures or visitor numbers to sensitive sites). It will also require making space for natural processes and possible site boundary changes; maintaining geodiversity so that a range of environmental opportunities remains available; and maintaining natural processes and the functional connectivity between different parts of geomorphological systems (e.g. between rivers and their floodplains). Essentially this means working with nature and natural processes.

3.2.3. Working with nature and natural processes

The principle of 'working with nature' is to maintain natural processes and their functions and to ensure that, as far as possible, natural systems and their components remain connected and are allowed to operate across their natural ranges of variability (Brazier et al., 2012; Cooper & McKenna, 2008). In management terms, this requires:

- making space to enable coasts, floodplains and slopes to evolve with minimal human intervention;
- maintaining or restoring natural processes such as flow regimes and sediment transport;
- utilising or restoring the natural functions of geomorphological processes and landforms (e.g. floodplains, wetlands and coastal beaches, dunes and saltmarshes) to enhance natural forms of flood management and coast defence;
- maintaining or restoring geomorphological connectivity in ecosystems, in river catchments and at the coast.

Working with nature helps to maintain geodiversity and landscape heterogeneity and, in turn, the diversity of habitats and natural processes that support biodiversity, including retaining natural habitats for native species and maintaining refugia and landscape connectivity for species to adapt to climate change. Maintaining and restoring dynamic systems that have greater natural resilience to climate change and sea-level rise also maximises nature conservation outcomes. This includes reconnecting rivers and their floodplains and maintaining mobility corridors (Choné & Biron, 2016; Opperman et al., 2009); utilising natural forms of coast protection and making space for migration of habitats through managed realignment (Arkema et al., 2013; Jackson et al., 2012; Leo, Gillies, Fitzsimons, Hale, & Beck, 2019; Nordstrom et al., 2011); and maintaining a diversity of habitat mosaics and disturbance regimes (Pander, Mueller, & Geist, 2018). A key aspect of such approaches is that management should be multifunctional, seeking to achieve complementary objectives for conservation of geodiversity, biodiversity and landscape diversity as well as delivering wider benefits for society such as flood risk management, carbon management and water supplies (Fig. 2D). If intervention is essential, then 'soft' methods are more sustainable than heavily engineered 'fix and control' measures that disrupt natural processes and have negative impacts both locally and further afield. Such measures include beach nourishment, coastal realignment and restoring coastal habitats such as saltmarsh or mudflats rather than emplacing 'hard' coast defence structures. Outside protected areas, 'hard' defences may be appropriate locally to protect high-value infrastructure; elsewhere, solutions that allow space for nature will be the only sustainable option, for example enabling landward migration of coastal wetlands. This will require integrating the socio-economic dimension (Chaffin & Scown, 2018; Schuerch et al., 2018; Silva et al., 2019) and working with governments, planners, policy makers and local communities to ensure that geodiversity and biodiversity form part of adaptation strategies (Brown, Prosser, & Stevenson, 2012; Prosser et al., 2010).

An important part of working with nature is to recognise landscape-scale connectivity at catchment, coastal zone or ecosystem scales and to consider how geomorphological changes in one part of a system will have impacts elsewhere (Knight & Harrison, 2013a). Therefore, management of part of a natural system should not be undertaken in isolation and should recognise the value of connectivity and the dependencies between different parts of the system at the landscape scale (e.g. downstream habitat changes arising from increased headwater slope erosion and changes in sediment transfer between hillslopes and river channels).

In many dynamic systems, working with natural processes may mean accepting the loss of some features, changes in their locations possibly outside the boundaries of the protected area, or their realignment, but may be the only effective sustainable approach. It will require reconsidering the management objectives of protected areas where some features are lost and/or processes altered. If the geomorphological processes that maintain habitat condition change, then conservation targets may no longer be viable in some protected areas. This may mean that the protected area status can no longer be justified or that site boundaries may need to be altered where dynamic features shift locations. Managing biodiversity adaptations therefore requires consideration of geomorphological sensitivity and making space for natural processes to readjust.

3.2.4. Learning from the past and applying understanding of physical processes and landscape evolution to inform restoration and adaptive management interventions

Conservation management of active systems should be based on a sound understanding of the underlying physical processes and landscape evolution (Gray et al., 2013). The physical landscape that forms the 'stage' for biodiversity is a complex system of geology, landforms and materials of different ages and origins, which has evolved over time and has varying characteristics, properties and capacity to absorb change (Thomas, 2012). Contemporary geomorphological processes are also conditioned by the landscape history and the physical template on which they operate. This is now being recognised in ecosystem-based approaches to the management of freshwater (Gurnell et al., 2015; Vaughan et al., 2009) and coastal (Jones et al., 2011; Temmerman et al., 2013) ecosystems and as part of river catchment and shoreline management plans, respectively. From a management perspective, the aim of learning from the past is not to provide static baselines, but to help understand past ranges of natural variability, landscape sensitivity and future trajectories of change.

Palaeoenvironmental records also have an important part to play in planning for change, assessing conservation management decisions and informing ecological restoration and indicating ecosystem service trends (Gillson & Marchant, 2014; Jeffers et al., 2015). Conservation of geosites with records of past environmental changes can ensure that such temporal records remain accessible for study and help to inform restoration and adaptive management.

4. Conclusions

1. Geoconservation management must primarily address the conservation of geoheritage. This requires the identification of sites that are managed according to sound geoconservation principles. There has been much focus on geosite selection, but this is not an end-goal; conservation management and monitoring are equally critical as part of geoconservation strategies at all levels from local to international. The IUCN *Guidelines on Geoconservation in Protected Areas* provides a reference source for site managers and advisors.
2. Many countries now have geoheritage site assessment programmes. However, conservation of geoheritage should be an integral part of protected area management, not only within stand-alone geosites, but also across all protected areas. This requires the identification and best-practice management of geoheritage interests and geosites within these areas. Although geosites are primarily selected for their geoscience value, they also have a wider range of educational, aesthetic, spiritual, cultural and ecological values that contribute to geoheritage and should accordingly be recognised in protected area management.
3. In view of the links between geodiversity and biodiversity, the conservation of geodiverse, heterogeneous landscapes (i.e. conserving nature's stage) should underpin the development of robust protected area networks that help to maintain the resilience and adaptive capacity of biodiversity in the face of climate change. This should help to maintain options for adaptation and relocation of species. It will be important to accept, however, that in many cases change will be inevitable, both in the properties and characteristics of the physical domain and in the species that occupy its diverse spaces.
4. Geodiversity is highly relevant to the wider nature conservation agenda. It is part of natural capital and provides ecosystem services that benefit nature and people. In the face of human pressures and climate change, geodiversity-informed strategies for the management of protected areas will be critical to deliver nature conservation goals and wider benefits for people, including essential contributions to sustainable development. A more integrated approach to protected area management through inclusion of geoconservation guiding principles and geoscience knowledge would benefit both biodiversity and geodiversity, while linking nature, culture and people should help to enhance the relevance of geoconservation to society.
5. Approaches based on the concepts of 'people and nature' and 'conserving nature's stage' provide opportunities to mainstream geoconservation in protected area management and environmental policy. The two approaches may be considered as complementary, as exemplified by the many ecosystem services and benefits provided by geodiversity, the role of working with nature and natural solutions in alleviating natural hazards and the contributions of geodiversity to sustainable development. In all these areas, more holistic approaches and interdisciplinary research linking geodiversity, biodiversity and people are essential.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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