Conservation Biology

Special Section

Why geodiversity matters in valuing nature's stage

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Abstract: *Geodiversity—the variability of Earth's surface materials, forms, and physical processes—is an integral part of nature and crucial for sustaining ecosystems and their services. It provides the substrates, landform mosaics, and dynamic physical processes for habitat development and maintenance. By determining the heterogeneity of the physical environment in conjunction with climate interactions, geodiversity has a crucial influence on biodiversity across a wide range of scales. From a literature review, we identified the diverse values of geodiversity; examined examples of the dependencies of biodiversity on geodiversity at a site-specific scale (for geosites <1 km^2 in area); and evaluated various human-induced threats to geosites and geodiversity. We found that geosites are important to biodiversity because they often support rare or unique biota adapted to distinctive environmental conditions or create a diversity of microenvironments that enhance species richness. Conservation of geodiversity in the face of a range of threats is critical both for effective management of nature's stage and for its own particular values. This requires approaches to nature conservation that integrate climate, biodiversity, and geodiversity at all spatial scales.*

Keywords: abiotic ecosystem services, biodiversity, geosite, cave, hot spring, metalliferous soils, threats to geodiversity

Por Qué Es Importante la Geodiversidad en la Valoración del Estado de la Naturaleza

Resumen: *La geodiversidad—la variabilidad de materiales, formas y procesos físicos de la superficie terrestre—es una parte integral de la naturaleza y es crucial para mantener a los ecosistemas y a sus servicios. Proporciona los sustratos, los mosaicos de accidentes geográficos y los procesos físicos dinámicos para el desarrollo y mantenimiento de los hábitats. Al determinar la heterogeneidad del ambiente físico en conjunto con las interacciones del clima, la geodiversidad ha sido una influencia importante sobre la biodiversidad a través de una gama amplia de escalas. A partir de una revisión bibliográfica, identificamos los valores diversos de la geodiversidad; examinamos ejemplos de las dependencias de la biodiversidad hacia la geodiversidad en una escala específica de sitio (para geositios < 1 Km^2 de área); y evaluamos varias amenazas inducidas por humanos para los geositios y la geodiversidad. Encontramos que los geositios son importantes para la biodiversidad ya que generalmente mantienen una biota rara o única, la cual está adaptada a condiciones ambientales características o la cual crea una diversidad de microambientes que mejoran la riqueza de especies. La conservación de la geodiversidad de cara a una gama de amenazas es crítica tanto para el manejo efectivo del estado de la naturaleza como para sus propios valores particulares. Esto requiere de enfoques para la conservación de la naturaleza que integran al clima, a la biodiversidad y a la geodiversidad en todas las escalas espaciales.*

Palabras Clave: amenazas para la geodiversidad, biodiversidad, cueva, geositio, manantial, servicios ambientales abióticos, suelos metalíferos

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Introduction

The fundamental assumption of the conserving nature's stage approach to maintaining biodiversity is that the physical environment constitutes a stage that will support the actors, the species that are the primary target of biodiversity conservation, even if the actors change due to climate change (Hunter et al. 1988; Anderson & Ferree 2010; Gill et al. 2015; Lawler et al. 2015). This assumption is based on the classic ecosystem concept in which biotic and abiotic components form an interacting system (Tansley 1935). We argue that geodiversity, including small sites that contain particular elements of geodiversity, merits conservation for its own values as well as its importance for biodiversity. First, we considered the diverse values of geodiversity from the perspective of ecosystem services. Second, we examined the interface of biodiversity and geodiversity through the lens of geosites, small geofeatures (< 1 km^2 in area) that are special environments for biota. The regional scale interface of geodiversity and biodiversity is covered in other articles in this special section (Anderson et al. 2015; Beier et al. 2015; Comer et al. 2015; Sanderson et al. 2015). Finally, we considered various human-induced threats to geosites and geodiversity.

Values of Geodiversity in an Ecosystem Context

Geodiversity is the variability of Earth's surface materials, landforms, and physical processes, for example, materials such as rocks, soils, and water; landforms such as mountains, glaciers, and lakes; and processes such as soil formation, coastal erosion, and sediment transport (Fig. 1) (Gray 2013). Geodiversity is widely recognized for its scientific value and the substantial knowledge benefits it provides for society (e.g., records of past climate changes, the evolution of life, and understanding of how Earth systems operate) (Gray 2013; Gray et al. 2013). However, in the last decade, there has been growing appreciation of the wider values of geodiversity and its links with landscape and biodiversity conservation, economic development, climate change adaptation, sustainable management of land and water, historical and cultural heritage, and people's health and well-being (Table 1) (e.g., Gordon et al. 2012; IUCN 2012; Gray 2013). These values are now embedded within the concept of ecosystem services (Millennium Ecosystem Assessment [MA] 2005). Without the contribution of geodiversity, many of the ecosystem services essential to life on the Earth would not exist or would require vastly expensive technological alternatives (e.g., provision of fresh water, regulation of water and air quality, and soil formation and nutrient cycling for food production). Geodiversity underpins or delivers directly most of the types of ecosystem services identified in the MA (Fig. 2) (Gray 2011; Gray 2012; Gordon & Barron 2013; Gray et al. 2013). It also provides additional indispensable goods (e.g., minerals, aggregates, and fossil fuels) that are usually considered to be nonrenewable capital assets (Gray 2013).

In the context of conserving nature's stage, geodiversity delivers many essential supporting services for biodiversity including providing the substrate and landform mosaics for the habitat development (static aspect), as well as the soil formation (e.g., Ibáñez et al. 2012; Ibáñez & Bockheim 2013), biogeochemical and water cycling, and geomorphological processes (e.g., water flow regimes, sediment supply, erosion, and deposition) for habitat maintenance (dynamic aspect). To some degree, all ecosystems owe their origins to the geological and geomorphological stage, from entire ocean basins and mountain ranges to small springs and rocky outcrops. As explored throughout this special section, "Conserving Nature's Stage," explicit measures of geodiversity may be among the more useful indicators for the distribution of biodiversity (Pressey et al. 2000; Anderson & Ferree 2010; Beier & Brost 2010; Hjort et al. 2012). For example, Schnitzler et al. (2011) founded a correlation between high geodiversity and biodiversity in a South African biodiversity hotspot. It is also important to emphasize that while many geofeatures such as bedrock geology and topography are stable relative to species distributions (e.g., Beier & Brost 2010), the stage is not simply a static entity and biodiversity is often maintained by dynamic physical processes from micro- to macroscales (Kozłowska et al. 2006; Pressey et al. 2007; Alexandrowicz & Margielewski 2010). For example, some insects rely on processes that continue to create bare soils and sediments on exposed riverine sediments or eroding soft cliffs (O' Callaghan et al. 2013).

Most geomorphological systems are dynamic, with active land-forming processes that differ in magnitude, rate, and location (Thomas 2001). Such complexity across both space and time can be crucial in maintaining biodiversity by determining the heterogeneity of the physical environment (Hunter et al. 1988; Burnett et al. 1998; Nichols et al. 1998). For example, on mountain slopes, the diversity of talus, debris flow, solifluction, frost weathering, snow avalanche, and deflation materials and processes creates mosaics of micro- and mesoscale topography and dynamic environments that support a range of species that would be absent without these processes (e.g., Jonasson et al. 2005; Alexandrowicz & Margielewski 2010). Such dynamic and complex mosaics provide opportunities for high species richness according to the intermediate-disturbance hypothesis (Fox 1981; le Roux & Luoto 2014). They may also help to future-proof ecosystems by conveying a form of spatial and temporal insurance in a changing environment (Tscharntke et al. 2012)

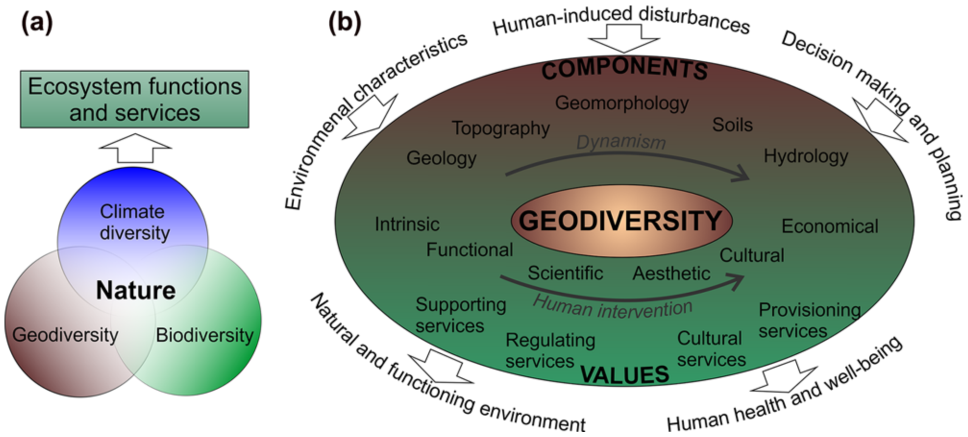

Figure 1. (a) Geodiversity's integral part of nature and importance to ecosystem functions and services (Gray 2011; Beggs 2013). (b) The main components and values of geodiversity and key influences (Gray 2013; Gray et al. 2013).

Table 1. Summary of the principal values and benefits of geodiversity (adapted from Gordon et al. [2012]).

Key values of geodiversity	*Geodiversity provides*
Maintaining life on Earth	the fundamental materials and hydrological and biogeochemical cycling to enable food and fiber production, provide clean air and water, construction materials, and energy sources
Underpinning biodiversity and landscape	the physical basis or stage (including natural processes) that supports most terrestrial, aquatic, and marine ecosystems and species and the physical basis of the character of valued landscapes (both rural and urban) and seascapes
Economic development	resources and assets for many aspects of economic development, including (geo)tourism-based activities and has a profound influence on the use of land and water
Knowledge of Earth history, materials, and processes	resources for scientific research and education and the knowledge base to help society adapt to climate change and to predict and mitigate natural hazards (including erosion, flooding, and slope failure)
Cultural inspiration	a powerful influence on cultural heritage through inspiration for art, sculpture, music, poetry and literature and on the character of the built environment through the use of different building stones
Recreation and health	a resource for a variety of recreation and outdoor activities and thus benefits for people's health and well-being

and enabling species to adapt or relocate through the availability of suitable environmental mosaics, connections, and elevational opportunities (Brost & Beier 2012).

Geodiversity also harbors information about past biodiversity (fossils, pollen, fungal spores) and about changing factors that affect biodiversity (e.g., climate change, volcanism, erosion, and sedimentation) (cf., Ackerly et al. 2010; Dobrowski 2011; Keppel et al. 2012). Landforms, sediments, and palaeoecological records all document past changes in ecosystems and their development over different timescales (Benton 2009; Hoorn et al. 2010; Schnitzler et al. 2011). While the past is unlikely to provide exact analogues for the future, palaeoenvironmental records have an important part to play in supporting conservation biology, not to provide static baselines or targets, but to inform understanding of ecological and evolutionary processes, ecosystem dynamics, and past ranges of natural variability (envelopes of change) (e.g., Willis & Birks 2006; Dawson et al. 2011; Gill et al. 2015). The long-term (decades to millennia) perspectives provided by palaeoenvironmental records can enable better understanding of trends in ecosystem services (Dearing et al. 2012; Gray et al. 2013), an acknowledged gap in the MA. For example, both paleo and recent data on river sediment loads can provide insights about the effectiveness of erosion control.

Geosites and Biodiversity Conservation

The interface between geodiversity and biodiversity mainly affects conservation planning at the landscape and regional scales as illustrated in other papers (e.g., Anderson et al. 2015). However, planning at these scales can overlook small geosites (usually <1 km^2) that may be very important to biodiversity, perhaps because they harbor a unique biota, such as cave-dwelling species (e.g., Culver & Pipan 2009; Pomory et al. 2011) or metallophytes (e.g., Baker et al. 2004; Whiting et al. 2004). (We also included shores and coasts—even though they are usually measured in linear kilometers—but have provided only a brief treatment here because their importance is already widely recognized in conservation planning and they are readily mapped.) Below and in Supporting Information, we briefly describe 18 types of geosites to

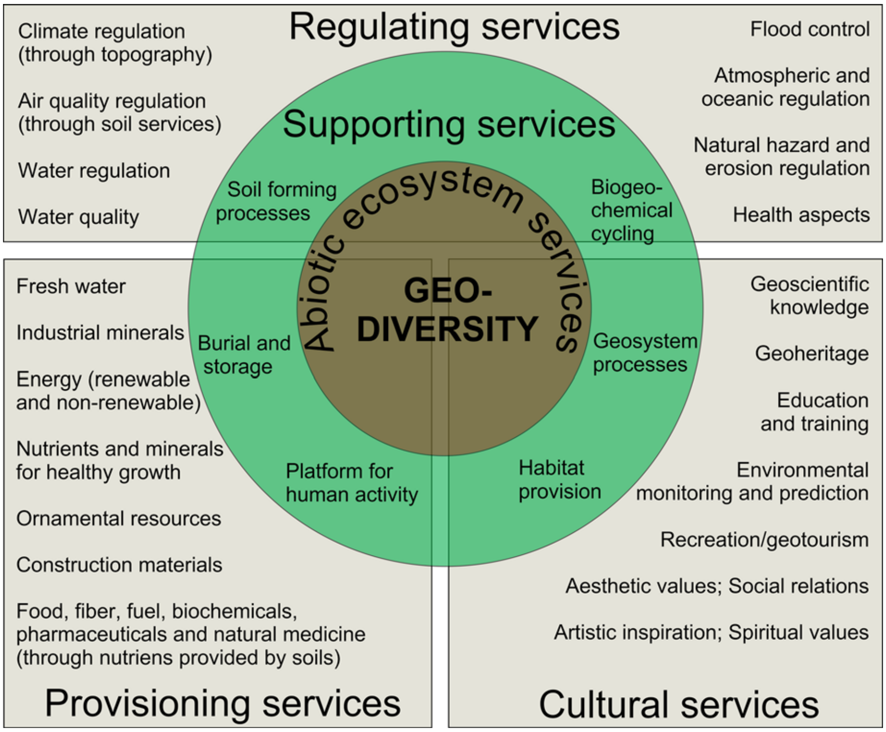

Figure 2. Summary of the ecosystem goods and services provided by geodiversity (Gordon & Barron 2013; Gray et al. 2013).

illustrate the concept. Our list is not exhaustive, but we used it to identify some important examples of geosites (Fig. 3). Moreover, the taxonomy we used is extremely subjective (e.g., all shores are lumped together, but we recognize 3 kinds of spring) but serves our purpose of illuminating the concept.

Caves

Naturally formed underground cavities are one of the clearest examples of why geodiversity is important to biodiversity because they harbor a highly distinctive biota adapted to life in darkness and relatively constant temperature and humidity (Culver & Pipan 2009). Different types of caves often hold a different biota because of variations in geological (e.g., volcanism and karst), hydrological (e.g., fluvial action of subterranean rivers), and biological processes (e.g., production of metabolic heat) (Fig. 3a). For example, anchialine caves contain a mixture of freshwater and saline water and often have a highly specialized fauna (Pomory et al. 2011). Furthermore, geographic isolation among cave systems can also generate a biota endemic to a limited region. Although cave ecosystems seem separated from the outside environment, they are often highly linked, for example, because of the movement of water or bats. Sometimes millions of bats have an ecological impact for many kilometers around a cave (Culver & Pipan 2009).

Cliffs

Variations in geology (e.g., rock type), size (from small rock outcrops to mountain faces), and aspect (which generates profound differences in microclimate [cf., Ackerly et al. 2010; Dobrowski 2011]) create distinct cliff habitats for biota that extend into the air above cliffs for aerial species (Larson et al. 2005; Kunz et al. 2008) (Fig. 3b). The dominant but invisible factor driving life on cliffs is gravity. This limits plant life to species that can cling to rocks and soil-filled crevices and animal life to species that can fly or climb very well. For both plants and animals, cliffs offer protection from some predators and competitors and this means some species (e.g., grazing-intolerant plants in areas otherwise subject to extensive grazing by domesticated animals) are usually found only on cliffs (Lambertucci & Ruggiero 2013). Cliffs also allow some species to reach extraordinary densities (e.g., thousands of seabirds nesting on a small cliff face [Larson et al. 2005]).

Limestone Pavements and Alvars

These calcium-rich environments with little or no soil, often due to its removal by glacial erosion, support grassland vegetation with a number of specialized plants, butterflies, ground-nesting birds, and snails. Particularly important are the moist and sheltered habitats in the cracks in limestone pavements (Fröberg et al. 2011) (Fig. 3c). Globally, these geosites are quite rare, mainly but not only limited to small sites in northern Europe and the Great Lakes region of North America.

Metalliferous Soils

These environments (e.g., serpentine and other ultramafic rocks) support metallophytes that are tolerant of

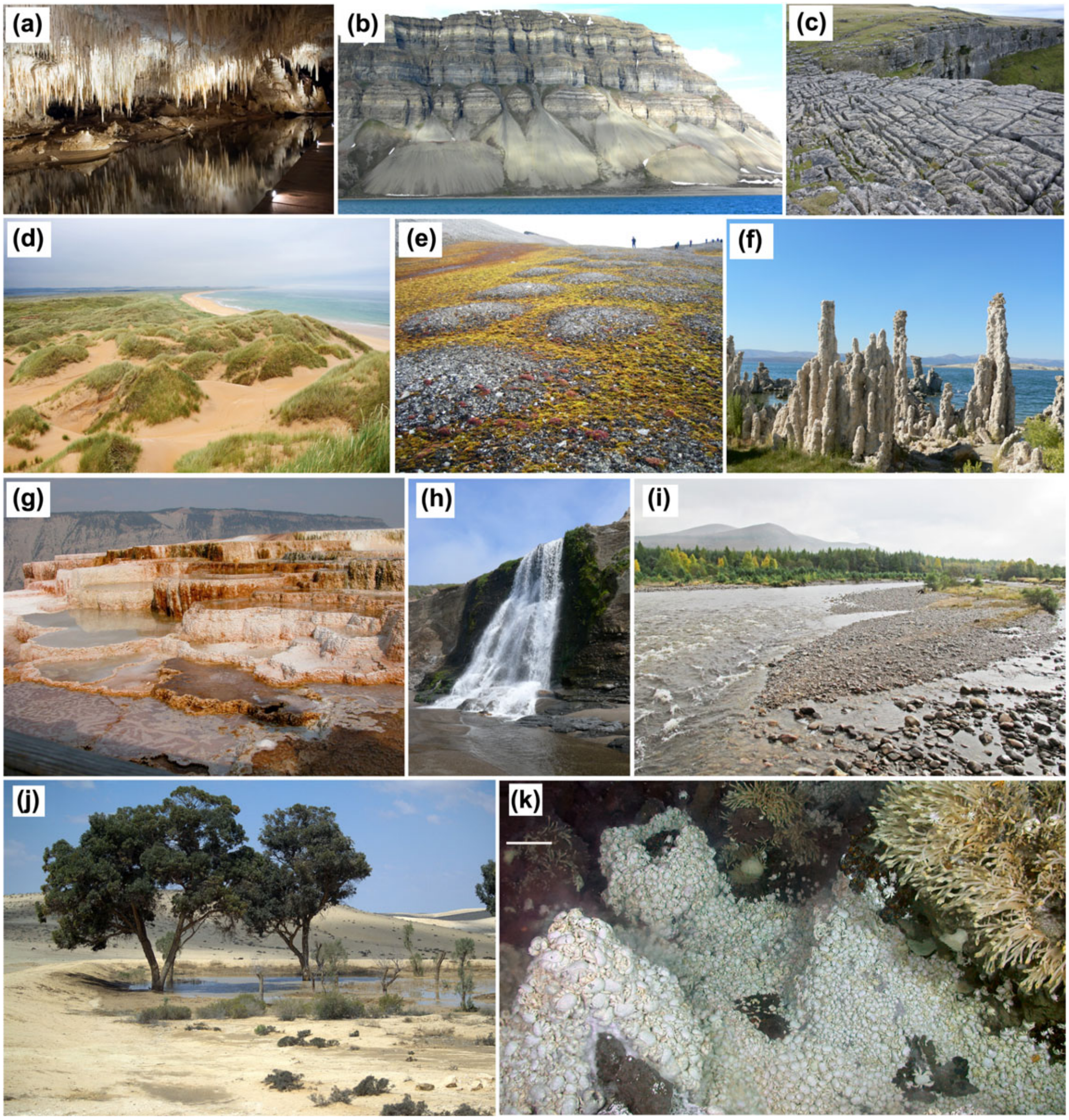

Figure 3. Examples of geosites and small geofeatures (< 1 km^2 in area) that are special environments for biota (photo credits in parentheses): (a) cave with stalactites and a subterranean stream in Western Australia (Wikimedia Commons, Paul Pickford), (b) cliff and talus cones in Svalbard, Norway (Wikimedia Commons, Wilson44691), (c) limestone pavement, Malham Cove, Yorkshire, United Kingdom (Murray Gray), (d) sand dunes in northeastern Scotland, United Kingdom (John Gordon), (e) patterned ground formed by frost processes on Cobourg Island, Nunavut, Canada (Flickr, Spencer Sweart), (f) tufa towers in Mono Lake, California, United States (Wikimedia Commons, Adrignola), (g) travertine terraces in Yellowstone National Park, United States (Flickr, Ildar Sagdejev), (h) Alamere waterfalls in California, United States (Wikimedia Commons, Renedrivers), (i) gravel river bar in Scotland, United Kingdom (John Gordon), (j) desert spring in the Negev Desert, Israel (Wikimedia Commons, David Shankbone), and (k) deep-sea hydrothermal vent with dense mass of the anomuran crab (Kiwa n. sp.) on the East Scotia Ridge, Southern Ocean (scale bar: 10 cm for foreground) (Wikimedia Commons, Papa Lima Whiskey 2).

low calcium:magnesium ratios and high concentrations of heavy metals such as copper, lead, nickel, and zinc (Green et al. 2003; Whiting et al. 2004). In addition to metal-tolerant plants, metalliferous sites may harbor rare bryophytes, lichens, and insects (Baker et al. 2004).

Talus (Scree)

Accumulations of weathered rocks, usually at the base of cliffs, provide cover for a number of species of small mammals, reptiles, amphibians, and invertebrates. Active talus slopes are harsh environments for biota due to dynamic processes and sometimes microclimate (e.g., cold air circulation) (Růžička et al. 2012). Instability can limit vegetation to species such as lichens and liverworts or species that can grow in a downward-shifting substrate (Fig. 3b).

Sand Dunes

Wind-driven (i.e., aeolian) sediments present a challenging environment for many plants but some species are able to thrive in these unstable environments and even stabilize them (Packham & Willis 1997) (Fig. 3d). The animal communities of dunes are largely dependent on whatever vegetation can develop (from sparse grass to woodlands), but a number of reptiles and arthropods, notably those that can readily burrow in sand, are confined to these settings (Barrows & Allen 2010).

Frost Sites

Frost- and slope-related periglacial processes generate fine-scale disturbances and microtopographical heterogeneity that shape plant communities (Fig. 3e). In highly active sites, frost processes create novel microhabitats for some plant species thus enhancing species richness of a given site (le Roux & Luoto 2014).

Snow Banks

Deep snow accumulations (i.e., nivation sites) can profoundly affect plant communities by limiting the stress of winter desiccation and cold, and summer droughts, but they also shorten the growing season. Due to the abundant soil moisture, weathering processes are active and produce fine-sediments and nutrients for plants (Björk & Molau 2007). These sites may also act as climate refugia for arctic and alpine species threatened by climate change (e.g., Dobrowski 2011; Keppel et al. 2012).

Temporary Pools

Pools that periodically dry out usually have a profoundly different biota from permanent water bodies (Williams 2006; Calhoun & deMaynadier 2008). This occurs primarily because very few fish species can persist during dry conditions and their absence, as predators and competitors, allows invertebrates and amphibians to flourish. Some plant species also do particularly well in sites that are periodically flooded because they are able to flourish in both the hydrological and the nutrient regime that develops when decomposition alternates between wet and dry. Notably, they are often highly integrated with surrounding ecosystems because of animal migrations (e.g., amphibians that move to pools to breed).

Tufa and Travertine

Calcium carbonate precipitation under relatively cool temperatures (e.g., in streams and lakes) generates tufa (Fig. 3f), whereas travertine is formed in warm or hot waters (e.g., hot springs) (Fig. 3g). They can be habitat for particular species of bryophytes, diatoms, and microbes (Ford & Pedley 1996).

Waterfalls

These are challenging places to live, but some species are able to occupy waterfalls, and thus, avoid competition or predation. In some settings, the high humidity generated by a waterfall is exploited by species living near, but not under, a waterfall (Zilihona & Nummelin 2001) (Fig. 3h).

River Bars

Sediment deposits along rivers are important resting and nesting sites for some birds, crocodilians, and turtles and are habitat for various insects and early successional plants (Fig. 3i). They may be more important when they form isolated islands (Larned et al. 2010).

Springs and Headwater Streams

Although often unknown, unnamed, and underappreciated, these tiny water bodies imbedded in a terrestrial environment can have a disproportionate ecological role because they are primary habitat for some species (e.g., certain insects, amphibians, molluscs, and plants) (Chaves et al. 2008) and are a water source for downstream aquatic ecosystems (Meyer et al. 2007). They are dynamic and diverse environments due to different hydrological (e.g., ephemeral versus perennial), geological (e.g., coarse- versus fine-grained sediments), and chemical (e.g., from alkaline to highly acidic) properties. For example, spring-fed headwaters are characterized by clear water and steady temperatures and flows, whereas rain-induced streams in dry environments are ephemeral with sediment-rich water (Larned et al. 2010).

Desert Springs

Springs in arid environments are particularly important for biodiversity because they are sometimes isolated from other water bodies, which can lead to the evolution of endemic species of fish, snails, crustaceans, and other species (Kodric-Brown & Brown 2007) (Fig. 3j). In some cases, animal populations for many kilometers around a desert spring are dependent on it for water during droughts, and if they are major herbivores this can have wide-ranging effects on vegetation (Valeix 2011).

Table 2. Principal human-induced threats to geodiversity and geosites and examples of impacts (adapted from Gordon & Barron [2011]; Brooks [2013]; Gray [2012]).

Threats	*Examples of on-site impacts*	*Examples of wider impacts on geodiversity*
Urbanization, construction (including commercial and industrial developments inland and at the coast, infrastructure) onshore windfarms and related activities	destruction of landforms, fragmentation of site integrity and loss of relationships between features, disruption of geomorphological processes, changes to soil and water regime	contamination of watercourses, changes to geomorphological processes downstream, arising from channelization of water courses or water extraction
Mining and mineral extraction (including extraction from opencast mines, pits, quarries, dunes and beaches, river beds, marine aggregate extraction and deep-sea mining)	destruction of landforms and exposures of sediments and rocks, destruction of soils, soil structure, and soil biota	changes in sediment supply to active process systems leading to enhanced erosion or scour in river and coastal systems, contamination of groundwater
Changes in land use and management (including agriculture, forestry)	landform damage through ploughing, ground leveling and drainage, soil erosion, changes to soil chemistry and soil water regime, soil compaction, loss of organic matter	increase in sediment yield and speed of runoff from catchments, episodic soil erosion leading to increased sedimentation and chemical contamination in rivers, lakes and caves, drying out of wetlands through local and distal drainage
Coastal protection and river management and engineering	damage to landforms and exposures of sediments and rocks, disruption of coastal and fluvial processes, inhibition of erosion allows exposures to become degraded	wider changes to sediment supply and transport, changes in process regime
Offshore activities (including dredging, trawling, renewable energy developments, hydrocarbon exploitation, and waste disposal)	physical damage to landforms and sediments, disruption of underwater physical processes, seabed and sub-seabed surface scour and penetration	changes to sediment movements and hydrodynamic processes
Recreation and geotourism	fragmentation of site integrity, footpath erosion and other localized soil erosion and loss of soil organic matter	
Climate change (especially in terrestrial environments)	changes in active system processes, changes in system state (reactivation or stabilization)	changes in sensitivity of land-forming environments (e.g., rivers, coasts) leading to changes in types and rates of geomorphological processes (e.g., erosion, flooding)
Sea-level rise	loss of visibility and access to coastal exposures and outcrops through submergence, loss of exposures through enhanced erosion	changes in wider patterns of erosion and deposition, enhanced flooding
Restoration of pits and quarries (including landfill)	loss of exposures and natural landforms	
Irresponsible fossil and mineral collecting	physical damage to rock exposures and loss of fossil record	

Hot Springs

Extreme temperatures limit the biota to microorganisms known as thermophiles, but this is a group of great interest to biologists as sources of heat-stable enzymes that are the basis for DNA technology and as models for what may have been the first life forms on Earth or other planets (e.g., Ward et al. 1998).

Shores

Shores and coasts, where the terrestrial, freshwater, and marine realms intersect, are manifestly important to biodiversity, arguably the most important places on the planet (Gray 1997). Here, many species reach their highest abundances because they are able to access resources from two realms, and many more are uniquely tied to the special conditions of these sites (e.g., the flood and ebb of water [at periodicities ranging from hours to decades, from tides to episodic floods] and the dynamism of substrates generated by erosion and sedimentation). The variability in multiple driving factors means that dozens of kinds of shores can be recognized, each with its own biota. Conservationists are well aware of the importance of shores, and their linear nature makes them generally easy to map for conservation planning (e.g., Gray 1997; Defeo et al. 2009).

Submarine Rock Outcrops

When isolated rock outcrops occur in an expansive bed of marine sediments (e.g., a seagrass bed), they often attract a diverse, abundant biota, most conspicuously fish that are different from species associated with mud or sand flats (e.g., Levinton 2001; McArthur et al. 2010). Thus, they substantially increase the beta diversity of a site. The importance of rock outcrops in marine systems is attested by the popularity of creating artificial reefs to increase fish populations.

Deep-Sea Hydrothermal Vents

These are among the most extreme geofeatures on the Earth. They have steep chemical, pH, and temperature gradients and extremely high pressure, and their complete darkness supports a unique food web based on chemosynthetic bacteria rather than photosynthesis. Diverse invertebrates (most notably tube worms and various crustaceans) depend directly on the bacteria, and various predators are supported too (Fig. 3k). Vents are continuously forming and breaking down through precipitation of minerals, earthquakes, and volcanic eruptions, and this dynamism tends to foster biodiversity because variations in the shape and size of deposits, as well as mineralogy, generate habitat diversity (Van Dover et al. 2002; Boschen et al. 2013).

Threats to Geodiversity

The threats facing geodiversity arise principally from development and land-use changes at both site and wider scales (Table 2) (Prosser et al. 2006; Stace & Larwood 2006; Gordon & Barron 2011; Gray 2013). The principal impacts are physical damage, loss of visibility or access, fragmentation and loss of relationships between features, and interruption of natural processes (e.g., river flow regimes and sediment cycling). Specific geofeatures may be affected by, for example, mineral extraction (e.g., metalliferous sites, limestone pavements), marine dredging, urbanization, agriculture (e.g., springs, temporary pools), bioprospecting (e.g., deep-sea hydrothermal vents, hot springs), and recreational activities (e.g., caves, cliffs, sand dunes) (Gray 2013). Indirect and off-site pressures may also arise from pollutants (e.g., by changing the chemical composition of both surficial and ground waters in caves and lagoons), climate change, and sea-level rise (Table 2) (Prosser et al. 2010).

While some rocks and landforms are relatively robust, degradation and loss of key sites is widespread (Gray 2013). Many features are relict or inactive and, analogous to species extinctions, once damaged or destroyed cannot be replaced. Thus, proactive conservation is essential to ensure the protection of geodiversity for its own direct values (Prosser et al. 2006; Gray 2013) and its interactions with biodiversity (e.g., Prosser et al. 2011; IUCN 2012). Many countries have introduced legislation to protect geosites, particularly in the developed world, and there is international recognition of geodiversity through, for example, the World Heritage and Global Geopark networks of sites (Global Geoparks Network 2013; Gray 2013; ProGEO 2013).

Conclusions

Geodiversity is crucial for sustaining living species and their habitats, and site-scale conservation targets are often unique due to geodiversity features. Thus, management of sites for biodiversity requires consideration of their geological and geomorphological setting, current state and past history and process dynamics. It is crucial that these aspects of the stage and their links to biodiversity are adequately understood as a basis for developing effective management responses to human pressures and climate change (e.g., Bruneau et al. 2011; Brazier et al. 2012). In many cases, maintaining natural processes will be a key part of conserving biodiversity (e.g., Hopkins et al. 2007; Pressey et al. 2007). Consequently, conservation management of the geodiversity components of the stage is crucial for sustaining species and ecosystems, particularly given the uncertainties about the effects of climate change (e.g., Bellard et al. 2012). At the same time, geodiversity merits conservation for its own considerable values. This requires much more integrated approaches to nature conservation planning and management—both biological and geological—at all scales from small sites to whole landscapes. Geodiversity in general, supported by geoconservation, delivers many fundamental ecosystem services, but this needs to be communicated much more effectively among disciplines, as well as between scientists and decision makers.

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Supporting Information

Examples of types of geosites and small geofeatures that are special environments for biota (Appendix S1) are available online. The authors are solely responsible for the content and functionality of the material. Queries (other than absence of the material) should be directed to the corresponding author.

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