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Conserving nature's stage provides a foundation for safeguarding both geodiversity and biodiversity in protected and conserved areas

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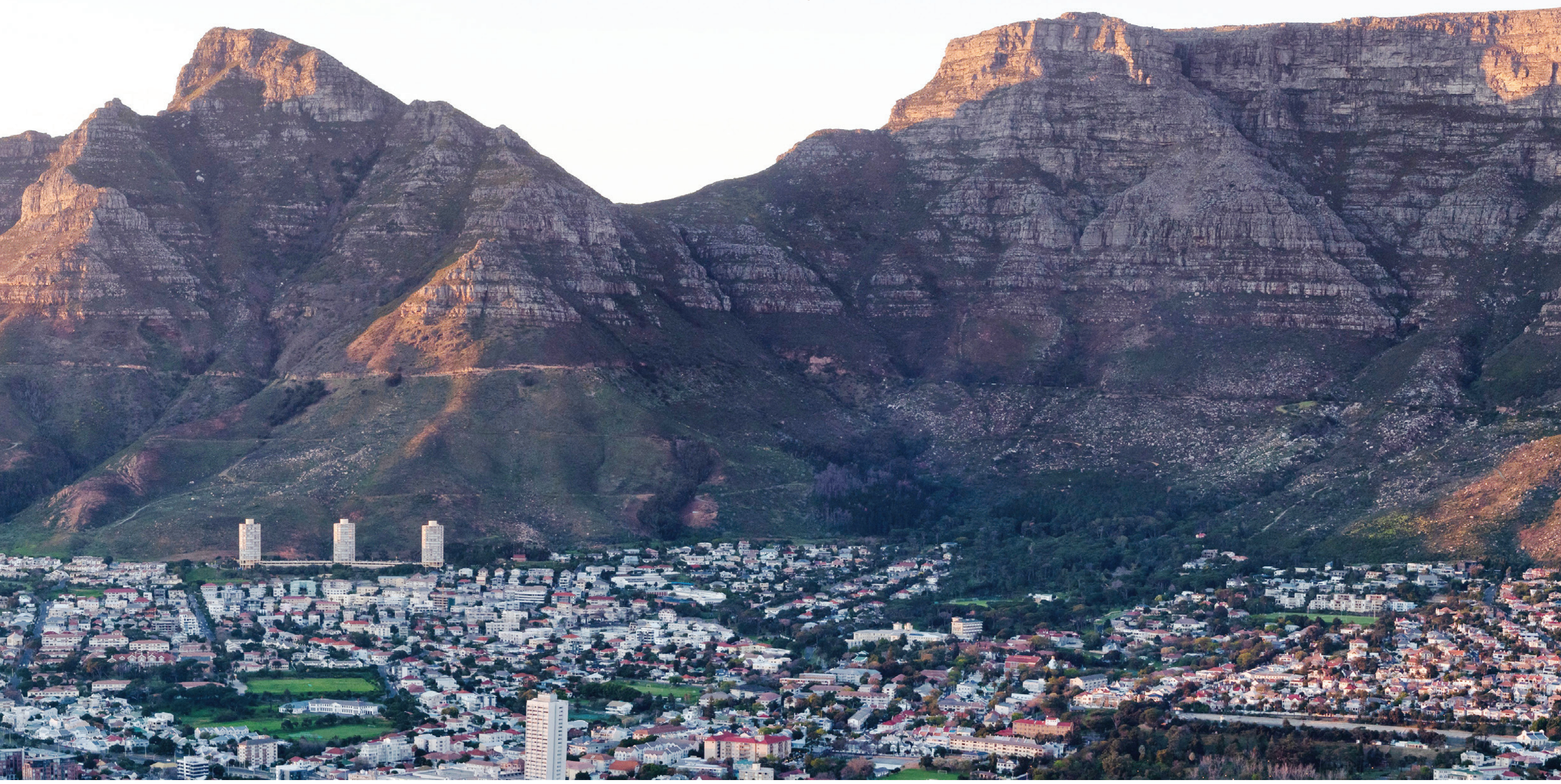


ABSTRACT

This article outlines the fundamental connections between geodiversity and biodiversity by providing a geoconservation perspective on the concept of "conserving nature's stage" as a basis for safeguarding both geodiversity and biodiversity in the face of environmental and climate change. Conserving nature's stage—the physical environment in which species exist—provides a means of developing more integrated approaches to nature conservation, delivering benefits for both geodiversity and biodiversity conservation, and incorporating key principles of geoconservation in the management of protected and conserved areas.

INTRODUCTION

The concept of "conserving nature's stage" (CNS) posits that conserving the physical template, or geodiversity, can contribute significantly to conserving nature in the face of environmental and climate change (Beier et al. 2015). It underpins a potentially important approach for bridging the gap in conservation between geodiversity and biodiversity.

This article provides a geoconservation perspective on the CNS approach. The aim is to encourage better integration of geodiversity into conservation planning and management of protected areas and within other effective area-based conservation measures (OECMs), both to advance geoconservation and benefit all of nature. The article first outlines

The geology of Table Mountain National Park, South Africa, supports internationally important fynbos vegetation. JEAN VAN DER MEULEN the concept of nature's stage and the fundamental links between geodiversity and biodiversity. It then examines the implications and benefits of the concept as a basis for practical conservation strategies in response to climate change, including the design of protected and conserved area (PCA) networks. An emphasis is placed on the value and benefits of more integrated approaches to nature conservation, both as a means to enhance conservation of abiotic nature and future-proof biodiversity as environments evolve and the climate changes.

GEODIVERSITY AS THE FOUNDATION OF NATURE'S STAGE

Geodiversity comprises the geological, geomorphological, pedological, and hydrological abiotic, or non-living, components of nature (Gray 2013). Its scope incorporates both static and dynamic components, ranging from topography, slopes, rocks, substrates, surface materials, and landforms, to soils and geomorphological and hydrological processes. Geodiversity occurs across all scales from global to local, and the geodiversity interest of an area can comprise a single feature or a diversity of features. The interactions of geodiversity and climate variables are vital for sustaining ecosystems, their biodiversity, and the services they provide (Hjort et al. 2015).

The concept of nature's stage has its roots in geoecology and the holistic, 19th-century view of Alexander von Humboldt that all nature is interconnected (Lawler et al. 2015). In its modern form, conserving the physical environment has been advocated as a coarse-filter approach to selecting PCAs to conserve a wide range of environments representing diverse abiotic conditions to enable species to adjust their distributions and to support future communities even if the species in those communities change (Beier et al. 2015). Underlying the concept is the metaphor that the physical environment is a "stage" upon which the species are the "actors" (Anderson and Ferree 2010; Beier and Brost 2010). As such, the physical template forms the foundations of most habitats in terrestrial and marine environments, acting as a supporting platform while providing hydrological, geomorphological, and biogeochemical processes essential for ecosystem functioning.

Many of the relationships between geodiversity and biodiversity are intuitive and well known (Lawler et al. 2015; Crofts 2019; Figure 1). For example, natural features such as cliffs, rock ledges, and caves may provide nesting or roosting sites for birds and bats, while in a functioning role, geodiversity is a critical factor in the process interactions and flows of minerals, water, and energy conditioned by bedrock lithology, the physical characteristics of the substrate, soil properties (e.g., texture, temperature, and moisture), landforms, topography, and geomorphological processes. Geodiversity underpins specialized habitats of exceptional ecological significance, such as those associated with limestone pavements, hot springs, or ultramafic serpentinite. Equally it underpins large-scale ecosystems across all latitudes and altitudes, such as those of glacial, fluvial, desert, and marine systems, providing the foundation for the diversity of landscapes and the connectivity between species, habitats, and ecosystems. The presence of individual features may also be significant, as well as their diversity (Hjort et al. 2015; Hunter et al. 2017). For example, the occurrence of rock outcrops, disused quarries, or inselbergs in otherwise relatively uniform landscapes or agricultural landscapes may have high biodiversity value.

Consequently, variations in biodiversity frequently reflect variations in geodiversity, so that geodiversity can be a good predictor of high biodiversity (e.g., Toivanen et al. 2019). Nevertheless, some qualifications are necessary. Some areas, such as active volcanoes and the forefields of retreating glaciers, can have high geodiversity but low biodiversity, although they may still be ecologically important, for example for pioneer species and colonization. Equally, some species distributions are driven primarily by biotic factors, such as disease, food, behavioral responses, and competition. Moreover, a species might not be able to disperse to favorable abiotic conditions provided by geodiversity, so it will not be found there. High-biodiversity areas or areas containing very rare species may also have low geodiversity (e.g., lowland tropical forests with simple topography and homogeneous surface materials), and we must be careful not to overlook such places when using geodiversity to identify conservation areas.

Nature's stage has both spatial and temporal dimensions. Spatially, links between geodiversity and biodiversity occur at all scales from global to local, modulated through interactions with climate variables. For example, global centers of vascular

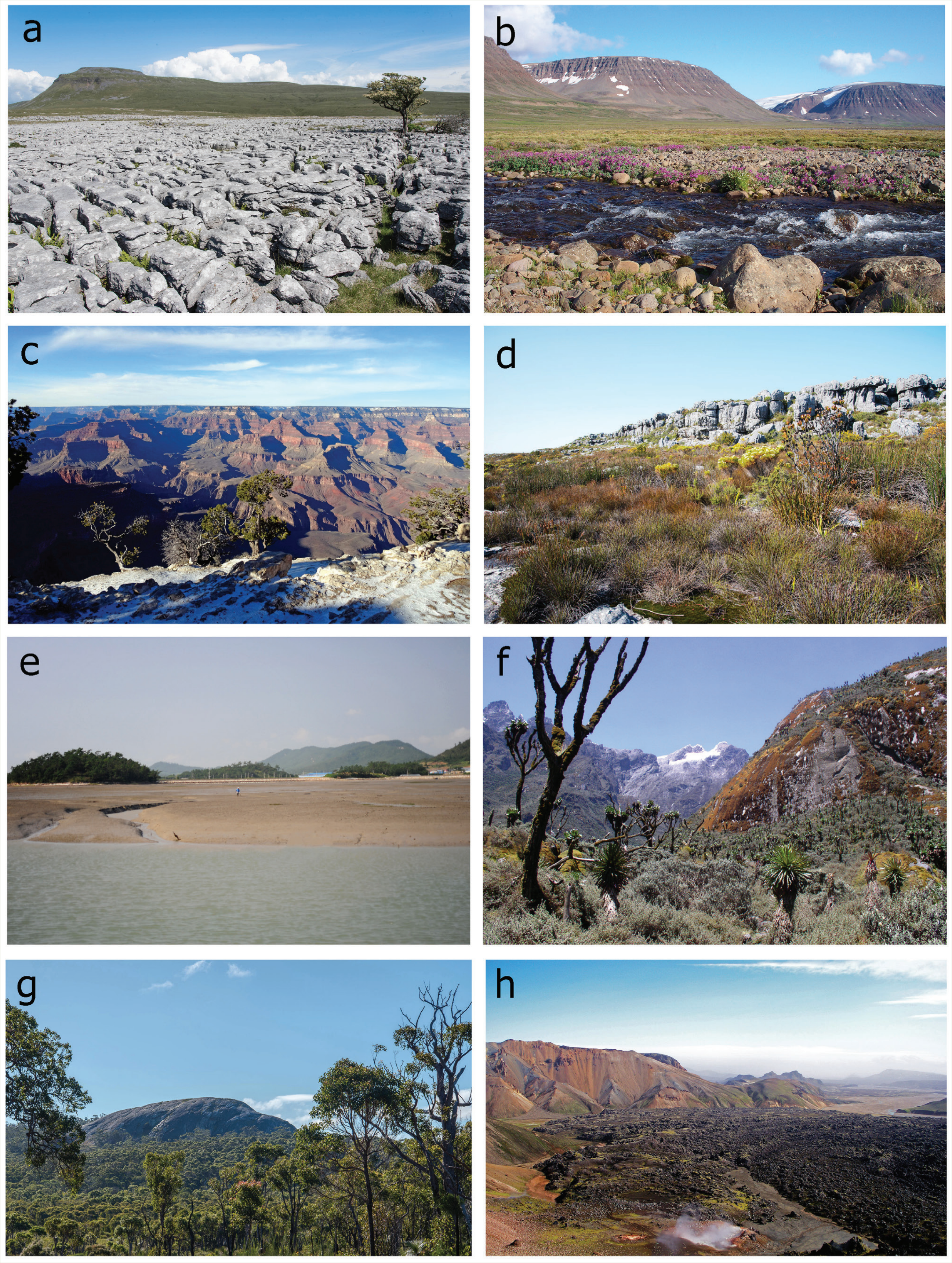


Figure 1. Examples of geological and geomorphological features that support biodiversity at different scales and in different environmental settings. (Caption continues on next page.)

Figure 1 (cont'd). Examples of geological and geomorphological features that support biodiversity at different scales and in different environmental settings.

a. Joints and fissures in limestone pavement in Ingleborough National Nature Reserve, northern England, provide habitat for vascular plants, bryophytes, lichens, and insects.

b. The landscape of Qeqertarsuaq (Disko Island), West Greenland, is dominated by Paleocene basalt mountains, plateaus, and steep glacial valleys with moraines, glacial outwash, and talus slopes, which support herb, shrub, heath, fellfield, and snowpatch vegetation on soils underlain by permafrost and subject to solifluction and frost disturbance.

c. The huge range in altitude and geology supports a variety of ecosystems in Grand Canyon National Park, USA, including riverine at the lowest elevations, through to boreal and pine forests at the higher elevations, as well as juniper woodland and deserts.

d. Table Mountain National Park, Republic of South Africa, forms part of the internationally important Cape Floristic Region. Geology, topography, and climate have played an important role in the evolution and distribution of the fynbos vegetation, mainly developed on nutrient-poor, acidic soils derived from the sandstone rocks that form the core of the park.

e. Getbol, Korean Tidal Flats World Heritage Site, Republic of Korea, represents an outstanding example of island-type tidal flats on the southwest coast of Korea, where a combination of geological, oceanographic, and climatic conditions has enabled the development of diverse coastal sedimentary systems that support high levels of biodiversity, including numerous endemic species of flora and fauna, and provide critical habitats for many migratory bird species.

f. The Rwenzori Mountains National Park and World Heritage Site, Uganda, is of outstanding importance for the altitudinal zonation of vegetation. The park comprises a block of Precambrian metamorphosed crystalline rocks uplifted above the surrounding plains during the formation of the Western (Albertine) Rift Valley in the Late Pliocene. High precipitation, cloud cover, and humidity, in conjunction with the mainly acidic soils and altitudinal range of topography, support the richest montane flora in Africa, including giant heathers, groundsels, and lobelias.

g. The granite inselberg of Mount Chudalup, in D'Entrecasteaux National Park, Western Australia, rises above a low-relief coastal plain covered in blown sand, sedge, and heathlands. Karri and marri woodland on loamy soils formed from weathered granite around the base of the inselberg is succeeded by peppermints, grass trees, snottygobbles, banksias, and sheoaks on sandier soils on the lower slopes and by numerous species of mosses, lichens, and liverworts on the upper slopes.

h. The geodiverse volcanic landscape of Fjallabak Nature Reserve, southern Iceland, includes the partly moss-covered Laugahraun lava field and provides specialized habitats for thermophilic bacteria and archaea associated with geothermal activity. IMAGES A, D, E, F, G, © JOHN GORDON; B, C, H © JOSEPH BAILEY

plants are located in mountain regions in the humid tropics where suitable climate conditions coincide with high levels of geodiversity. Meanwhile, at a finer scale, landforms, microtopography, soils, and geomorphological processes such as solifluction support a diversity of habitats and species.

Geodiversity is also the basis of landscape heterogeneity. Areas with high geodiversity provide a range of topographic and environmental mosaics, corridors, and refugia that can enable species and communities to persist, adapt, or relocate where there is suitable connectivity within and between different landforms and geomorphological systems. Geomorphological processes and disturbance regimes help to maintain or increase landscape and habitat heterogeneity, a key factor in enhancing resilience. Geodiversity also provides potential refugia, although these may be only temporary buffers for existing species and communities, or their role may be diminished if the speed of geomorphological change is too fast for species to adapt or relocate.

Temporally, landforms (and their associated ecology) also evolve over different time scales. For example, long-term geological (tectonic) processes, in conjunction with climate, have profoundly influenced ecosystem evolution in mountain areas such as the Andes and Himalayas. Over shorter time scales, as climate changes, shifts in the magnitudes and frequencies of geomorphological processes and their associated disturbance regimes may increase or decrease landscape heterogeneity as well as recovery times following major land-shaping events such as floods or slope failures. For example, under climate change, glacier retreat and permafrost thaw are accompanied by exposure of bare ground and enhanced paraglacial process activity, with consequent impacts on landscape heterogeneity, habitats, and biodiversity; at the coast, rising sea levels may result in geomorphological changes that are too rapid for existing coastal land systems or ecosystems to absorb, leading to major readjustments in coastal alignment and habitat distributions; while changes in catchment hydrology, water flow regimes, and discharges of sediment will alter hydrogeomorphology process zones and floodplain heterogeneity and thus habitat distributions and conditions. In all of these situations, the feedbacks between soils, geomorphology, and vegetation may modulate consequent landscape changes.

CONSERVING NATURE'S STAGE AS A STRATEGY FOR RESPONDING TO CLIMATE CHANGE

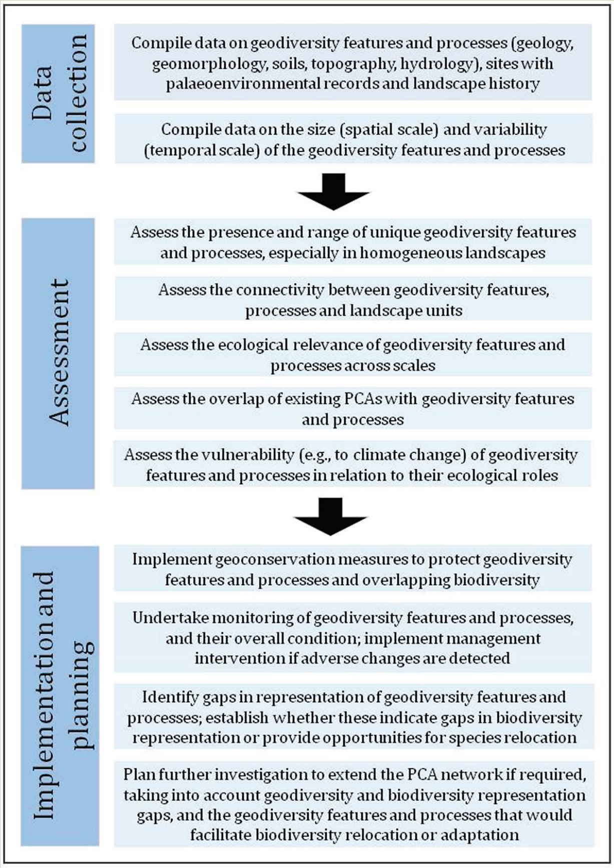
Under a changing climate, community compositions and species ranges will change over time, ecosystems will evolve, and new ecosystems are likely to develop. This means that in many cases CNS and a management focus on conserving ecosystem functions and evolutionary processes will be more effective in the longer term than trying to preserve the status quo. CNS also offers a holistic approach, integrating geodiversity into conservation planning as part of the design and management of PCA networks future-proofed against climate change. This benefits both geodiversity and biodiversity.

CNS contributes to planning for change, enables the identification of gaps or biases in PCA representation and potential localities for new PCAs as species ranges change (Anderson et al. 2014), and enables the progression of ecological and evolutionary processes both in response to environmental change and as the more dynamic components of geodiversity adjust. Consequently, some geodiversity-based PCAs will be relatively stable and resilient to climate change, enabling existing species to persist or adapt slowly and evolve over time, whereas others will be sensitive, requiring different conservation strategies and goals where change in the stage may be more rapid and connectivity will be important if existing communities are to be able to move and adapt (Comer et al. 2015). Understanding geomorphological sensitivity and landscape history will therefore be essential to assist conservation planning in such situations. In more sensitive and susceptible landscapes, there will need to be greater focus on maintaining or restoring ecosystem resilience and connectivity, where practical (Comer et al. 2015).

CNS has the potential to protect a wide range of abiotic conditions and biotic associations, as well as facilitating movement of species between particular places, through availability of surface materials, hydrological features, and a range of temperatures due to different slopes, aspects, elevations, and landform microclimates, for example. Boxes 1 and 2 illustrate the practical benefits of CNS at different spatial scales in very contrasting environments (urban and montane). Existing protected area networks are likely to already broadly represent substantial abiotic diversity, but the CNS approach, through mapping and integrating geodiversity and environmental heterogeneity, may help to highlight areas that are under-represented and assist prioritization of future efforts as species track suitable abiotic conditions across (e.g., latitudinally or altitudinally) and within (e.g., according to microclimatic conditions and local geology, soils, and landforms) landscapes as the climate changes.

In terms of practical applications of CNS, Comer et al. (2015) examined how integration of geodiversity could improve decision-making in the assessment, planning, implementation, and monitoring stages of PCA management, while Anderson et al. (2015) reviewed eight case studies of conservation plans that incorporate geodiversity and showed how this can enhance biodiversity-based approaches. Key considerations are the choice of geodiversity variables, land units, and assessment methods, and evaluation of connectivity between sites. As a practical tool to assist conservation managers, we propose an indicative workflow framework (Figure 2). Specialist geoscience input will be required, particularly in compiling a geodiversity inventory, but in subsequent steps a multidisciplinary

Figure 2. Indicative framework showing how protected area managers might integrate geodiversity as part of a CNS approach.



Compile data on geodiversity features and processes (geology, geomorphology, soils, topography, hydrology), sites with palaeoenvironmental records and landscape history

Compile data on the size (spatial scale) and variability (temporal scale) of the geodiversity features and processes

Assess the presence and range of unique geodiversity features and processes, especially in homogeneous landscapes

Assess the connectivity between geodiversity features, processes and landscape units

Assess the ecological relevance of geodiversity features and processes across scales

Assess the overlap of existing PCAs with geodiversity features and processes

Assess the vulnerability (e.g., to climate change) of geodiversity features and processes in relation to their ecological roles

Implement geoconservation measures to protect geodiversity features and processes and overlapping biodiversity

Undertake monitoring of geodiversity features and processes, and their overall condition; implement management intervention if adverse changes are detected

Identify gaps in representation of geodiversity features and processes; establish whether these indicate gaps in biodiversity representation or provide opportunities for species relocation

Plan further investigation to extend the PCA network if required, taking into account geodiversity and biodiversity representation gaps, and the geodiversity features and processes that would facilitate biodiversity relocation or adaptation approach involving geoscientists, ecologists, and conservationists is essential. In developing the approach, further empirical work and evaluation of different geodiversity variables in different situations are required (Alahuhta et al. 2020).

BENEFITS FOR GEODIVERSITY AS WELL AS BIODIVERSITY

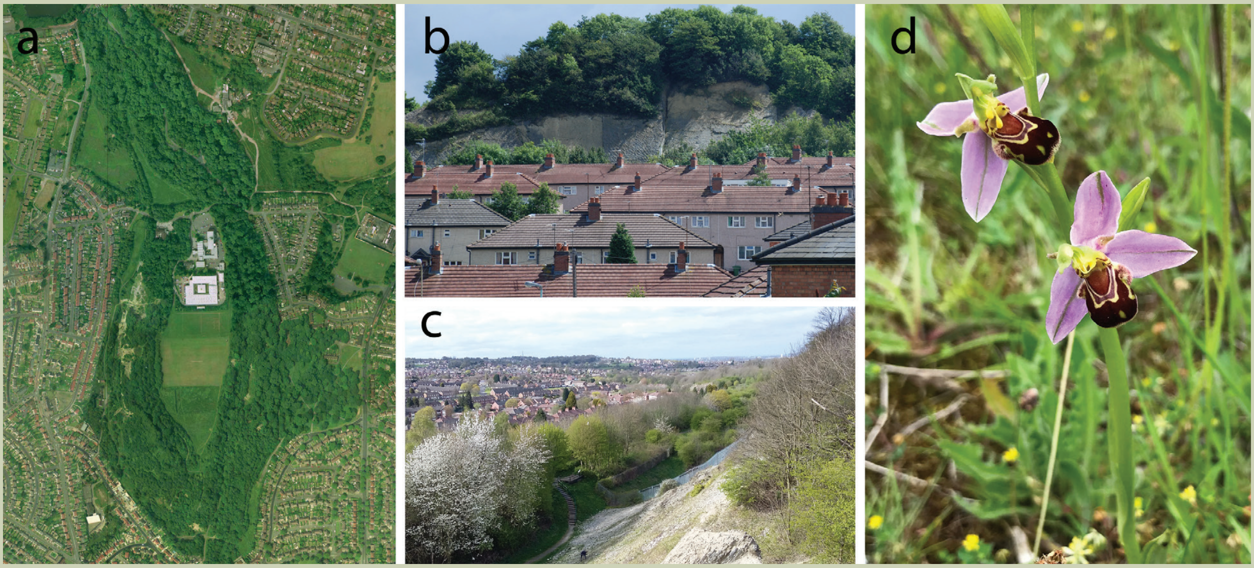
Conserving nature's stage and more integrated approaches that recognize the connections between geodiversity and biodiversity deliver benefits for both, as exemplified in Boxes 1 and 2 and in the

Box 1. Wren's Nest National Nature Reserve, Dudley, West Midlands, UK

Wren's Nest National Nature Reserve (NNR) ($0.34 km^2$) is one of three isolated and wooded Silurian Limestone hills in a densely urban area of the West Midlands in the United Kingdom. It is managed primarily as a geological NNR to maintain a network of accessible limestone exposures, particularly noted for their diverse fossil reef fauna. The site demonstrates the potential of the CNS approach for conserving both geodiversity and biodiversity.

Wren's Nest NNR exposes a network of interbedded, massive-to-flaggy limestones and shales with an associated free-draining calcareous substrate. The limestones are folded, creating steeply inclined limestone beds that were both quarried and mined during the 19th-century Industrial Revolution. A network of disused linear quarries and deep limestone mines and caverns (connected to the surface) provides extensive rock outcrops. The geological stage accommodates a calcareous flora and associated fauna, supports habitat diversity from open bare-ground to woodland, and provides a network of potential roost and nest sites for birds. Wren's Nest NNR is effectively a small-scale inselberg in an urban environment. If left unmanaged, Wren's Nest would be dominated by woodland with little open habitat. The existing woodland is dominated by ash, which prefers the well-drained soil typical of limestone substrates.

Geoconservation management at Wren's Nest includes maintaining a physically and visually accessible network of key exposures in the Silurian Limestone sequence. These exposures, including bedding plane



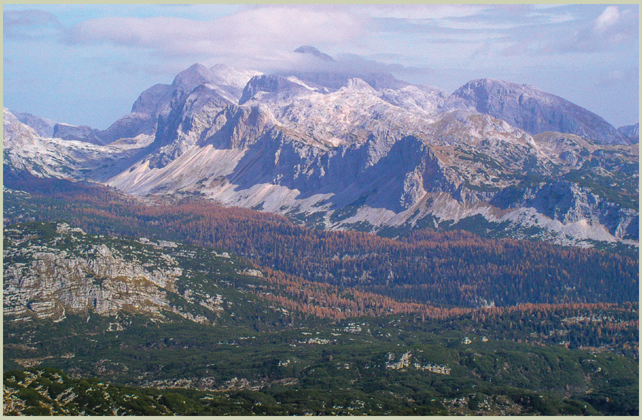
a. Aerial view of Wren's Nest NNR and surrounding housing estates. **b.** View looking eastwards from Wren's Nest housing estate to the prominent wooded hill of Wren's Nest NNR. **c.** View looking north westwards across Wren's Nest housing estate and the steeply dipping bedding plane exposures of the Silurian Upper Quarried Limestone. **d.** Bee orchid. © JONATHAN LARWOOD and vertical sections through the complete Silurian sequence on both sides of the hill, are kept accessible to the public by maintaining open vistas along the disused linear quarries (Upper and Lower Quarried Limestones). Effectively, this creates a series of open woodland rides (access corridors) through the NNR—bare ground and open habitat suitable for limestone grassland (which would not otherwise be present). There is engineered access to the underground mines and caverns, which have become a significant bat roost and hibernaculum accommodating eight recorded bat species that use the managed quarries/woodland rides as foraging routes through the NNR connecting to linear routes (especially canals) and other reserves beyond Wren's Nest. There is an established and expanding limestone grassland (with notable orchid populations, including bee orchid) on the NNR as a consequence of maintaining bare ground and woodland-free areas managed as meadows. There is an associated invertebrate fauna, with 25 butterfly species recorded (e.g., marbled white, which is typically associated with limestone grassland).

Overall, the result of managing geodiversity—nature's stage—at Wren's Nest NNR through maintaining and increasing accessible rock exposures, in conjunction with sympathetic habitat management, has been to increase both habitat and species diversity, which otherwise would not have occurred.

Box 2. Triglav National Park (Triglavski narodni park), eastern Julian Alps, Slovenia

Karst geology dominates Triglav National Park (TNP), providing a range of unique geodiversity features, as well as those that are familiar in most mountain ranges across the world. The TNP website highlights the links between biodiversity and geodiversity, stating: "The diversity of geological phenomena and processes is outstanding and provides the basis for the equally exceptional biodiversity of the area" (https://www.tnp.si/en/learn/majestic-mysterious-and-magical/geology/). Triglav, the eponymous mountain that also features on the Slovenian flag, is the national park's highest mountain (2,864m), giving way to valleys and foothills towards the outer areas of the national park.

When assessing the ecological relevance of geodiversity features, positive and negative effects for species and overall biodiversity must be considered, as too must the spatial scale of geoconservation efforts. At the scale of the whole park (848km²), the topographic range provides a variety of climatic conditions, which in conjunction with the geology and landforms supports a range of habitats and refugia, ranging from forests and peat bogs to meadows, lakes, and limestone cliffs and screes. Geoconservation at this scale should aim to maintain the integrity of the geodiversity features present both as the foundation of landscape heterogeneity and to ensure the connectivity between different components of the geodiversity (e.g., the hydrological connections between lakes and rivers), thereby sustaining habitat diversity and enabling species mobility and provision of refugia. More localised geoconservation measures to protect features such as limestone outcrops, scree slopes and caves should ensure that their ecological relevance is also protected.



Limestone mountains, cliffs, screes, plateaus, and valleys in Triglav National Park, Slovenia, provide a diversity of alpine karst habitats that support dwarf pines, alpine grasslands, Mediterranean pine forests, and other species adapted to calcareous environments. © JOHN GORDON alignment with key geoconservation principles and recommendations for best practice management in PCAs (Crofts et al. 2020).

First, the conservation of geodiversity as a platform for biodiversity requires identifying and protecting: (i) natural features (including geoheritage sites) and geomorphological process systems that provide a range of habitats (with local habitat connectivity); (ii) geodiversity hotspots; (iii) areas that are representative of a region's geodiversity as a foundation for its biodiversity; and (iv) sites with key paleoenvironmental records.

Second, it requires integration of geodiversity into landscape-scale conservation measures, connectivity planning, and design of corridors for management of natural systems in a spatially integrated manner, recognizing the catchment-wide or coastal-cell connections of geomorphological processes (Crofts et al. 2020). Connectivity planning should be integrated both as a platform to support the movement of species (and therefore biodiversity as a whole) and for geomorphological processes linking different landscape units.

Third, learning from the past and applying understanding of the geomorphological evolution and paleoenvironmental history of a region is vital in evaluating the sensitivity of the landscape to drivers of change and responses to geomorphological disturbance regimes arising from climate change. Paleoenvironmental records can also illuminate trends in species composition and ecosystem development in response to past climate change, disturbance from geomorphological processes and human activities, climate envelopes for different species, and natural variations in species ranges (Fordham et al. 2020). Such records are also increasingly crucial to informing habitat and ecosystem restoration, particularly where human intervention has led to change. Protection of sites with such records therefore benefits conservation of both geodiversity and biodiversity interests.

Fourth, understanding geodiversity and its interactions with biodiversity as part of working with nature is a key management principle for adapting to climate change and mitigating natural hazards. Such nature-based solutions implemented as part of CNS require recognizing the inevitability of natural change and planning for it based on understanding natural processes and making space for them to operate; for example, restoring natural flow regimes and reconnecting rivers and their floodplains as part of natural flood management, and maintaining sediment supply or implementing managed realignment at the coast usually through setting back or removing flood defenses and allowing the development of salt marshes to attenuate wave energy and trap sediment (Crofts et al. 2020). This requires assessing the sensitivity and vulnerability of geomorphological features and systems and managing them within the limits of their capacity to absorb change insofar as pressures and threats can be controlled (e.g., through visitor management).

Fifth, conservation of geodiversity through CNS contributes to maintaining the benefits of the many ecosystem or geosystem services delivered by geodiversity (Gray 2013, this issue). For example, geodiversity provides fresh water and minerals, regulates climate and water processes, supports habitats and nutrient cycling, and is appreciated for its cultural values, including for artistic inspiration, recreation, and geotourism.

Finally, since many areas of geodiversity value face pressures and threats from a range of human activities (Hjort et al. 2015; Crofts et al. 2020), their safeguarding as part of multiple-interest PCAs will make a significant contribution to geoconservation as well as enhancing nature conservation in the face of increasing homogenization of biodiversity from climate and land-use changes (Newbold et al. 2019).

CONCLUSIONS

CNS is predicated on the close interconnections between geodiversity and biodiversity; in particular, the dependence of many species and communities on specific geological, geomorphological, edaphic, and topographic factors interacting with climate conditions. The conservation of geodiverse areas with a wide a variety of environmental conditions is a practical, coarse-filter approach to safeguarding both geodiversity and biodiversity in the face of environmental and climate change. As well as building future species distributions into conservation planning, CNS provides a means of incorporating complementary geoconservation objectives, with consequent benefits for nature conservation as a whole, including facilitating climate change adaptations and maintaining key ecosystem and geosystem services. It encourages a holistic approach, incorporating geodiversity and geoconservation best practice and principles into conservation planning and management. Furthermore, CNS recognizes the inevitability of change and allows for geomorphological systems, ecosystems, and species to evolve along with climate and other abiotic factors.

Conservation of geodiversity should therefore be an integral part of conservation planning as part of a holistic approach to nature conservation—not all geodiversity, which is clearly impractical, but where it supports geoheritage, ecological, and cultural values. This should include PCA networks founded on geodiversity both as a platform for biodiversity and for sustaining key geomorphological and ecosystem processes into a changing and uncertain future. In this way, maintaining geodiversity should contribute to the resilience and adaptive capacity of the biosphere.

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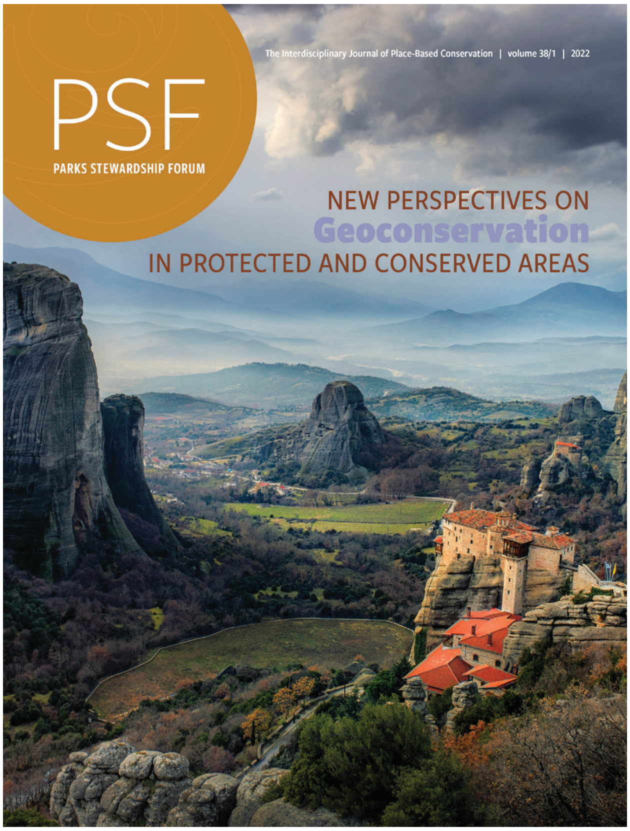

On the cover of this issue

The precipitous rock spires of Meteora World Heritage Site in Greece have a complex geological history. Over the centuries a number of Eastern Orthodox monasteries were built atop them, and today's World Heritage Site recognizes this cultural history as part of the overall geoheritage. | STATHIS FLOROS