Acknowledging geodiversity in safeguarding biodiversity and human health

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Our existence on Earth is founded on a vital nature, which supports human physical and mental health. However, nature is often depicted only through biodiversity, whereas geodiversity—the diversity of non-living nature—has so far been neglected. Geodiversity consists of assemblages, structures, and systems of geological, geomorphological, soil, and hydrological components that fundamentally underlie biodiversity. Biodiversity can support overall human health only with the foundation of geodiversity. Landscape characteristics, such as varying topography or bodies of water, promote aesthetic and sensory experiences and are also a product of geodiversity. In this Personal View, we introduce the concept of geodiversity as a driver for planetary health, describe its functions and services, and outline the intricate relationships between geodiversity, biodiversity, and human health. We also propose an agenda for acknowledging the importance of geodiversity in health-related research and decision making. Geodiversity is an emerging topic with untapped potential for ensuring ecosystem functionality and good living conditions for people in a time of changing environments.

Introduction

The coexistence of human health and wellbeing with viable ecosystems is the cornerstone of sustainable living on Earth.[1] This association is underscored by the UN's Sustainable Development Goals, which pursue nature conservation as well as equality and sustainability among people, societies, and cities. However, our ability to reach these important goals is hindered by the degradation of living nature (ie, biodiversity founded on flora and fauna) and non-living nature (ie, geodiversity founded on geology, geomorphology, topography, soils, and hydrology) that results from global change caused by human activities. Such degradation also poses severe threats to human health and wellbeing, which are highly dependent on nature.[2]

Our knowledge of the benefits of nature for both physical and emotional health is accumulating steadily.[3–9] The variety of living nature at genetic, species, and ecosystem levels is known as biodiversity. Biodiversity contributes to the quality of nature, as a more diverse biotic environment can provide a greater variety of ecosystem functions and services.[10] Increasing scientific evidence shows that biodiversity contributes to human physical and mental health through various pathways and processes.[7,11,12] However, biodiversity is an over-simplified view of nature, because by focusing only on biodiversity we neglect the diversity of the non-living components of the Earth's surface and subsurface, namely geodiversity.[13] The importance of geodiversity for nature conservation and ecosystem service provision has been relatively neglected until recently.[14–16] Geodiversity can contribute substantially to biodiversity and human health; however, the pathways and processes by which this occurs have not been sufficiently explored or empirically tested (panel).

Geodiversity is commonly defined as the natural variety of geological (ie, rocks, minerals, and fossils), geomorphological (ie, landforms, topography, and physical processes), soil, and hydrological features or, more generally, the non-living diversity of the Earth's surface and subsurface.[13] This diversity includes the assemblages, structures, and systems of these features and their contributions to landscapes. Examples of geodiversity range from fossils of dinosaurs, quartz minerals, and freshwater ponds to the eruption of

Panel: Key messages on relationships between geodiversity, biodiversity, and human health and wellbeing

- Human health and wellbeing are highly dependent on diverse nature, which is often portrayed only through biodiversity. However, by narrowly focusing on biodiversity, we ignore the non-living components of nature (ie, geodiversity).
- Geodiversity—the diversity of Earth's surface and subsurface materials, landforms, and processes—is a core component of the overall viability of nature, and a crucial factor in providing different types of ecosystem service. Human activities, such as mining and land-use change, pose a severe threat to geodiversity.
- Geodiversity and biodiversity are inherently interlinked. Biodiversity cannot foster human physical and mental health without the supporting role of geodiversity. Non-living nature also offers landscape characteristics, which provide aesthetic and sensory experiences.
- Although geodiversity is essential to biodiversity and human health across populations and societies, more research is needed to comprehensively understand the multiple pathways and processes that govern relationships between geodiversity, biodiversity, and human health. With a better understanding of these associations, geodiversity could be integrated into spatial planning, environmental conservation, and management actions, and public health decision making.

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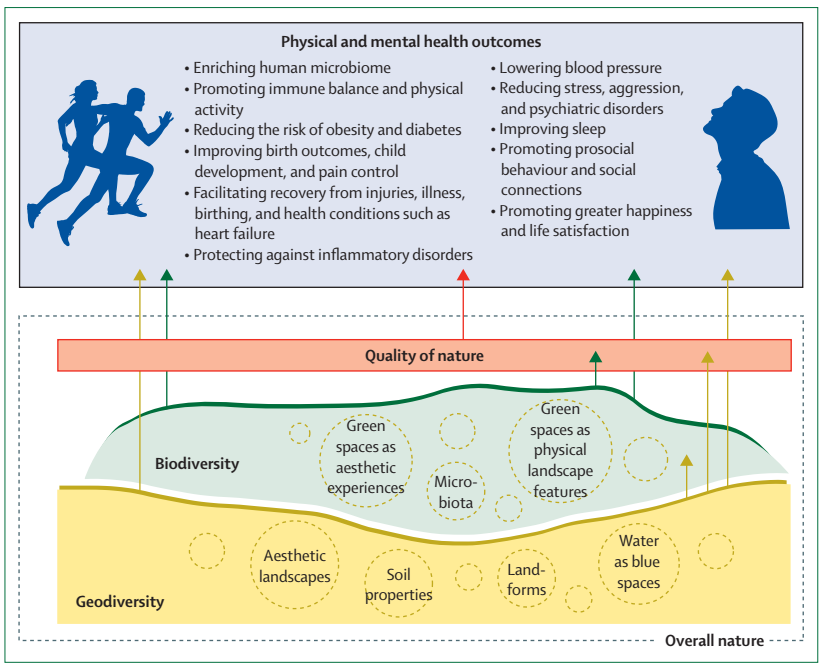

Figure 1: **How geodiversity underlies biodiversity and modifies the quality of nature, thereby indirectly and directly contributing to human health**

For the **Common International Classification of Ecosystem Services** see https://cices.eu/

magma-filled volcanoes and eskers with sorted moraine soils originating from the ice ages. Simply, geodiversity is seen as the non-living equivalent of biodiversity. Like foundation and keystone species, which have an exceptional ecological role in the functions of ecosystems,[17,18] particular components of geodiversity can contribute considerably to both biodiversity[19–21] and human health and wellbeing.[11] Together, geodiversity and biodiversity contribute to ecosystem maintenance and functionality, which create foundations for human existence on Earth (figure 1). However, we lack in-depth knowledge and resources to fully understand the benefits of geodiversity for human and planetary health. Here, we propose a framework of the pathways and processes through which geodiversity can benefit human health and wellbeing across populations and societies.

Geodiversity framework in the era of global change

Geodiversity forms a basis for biological diversity as it provides the physical settings in which species can exist.[22–24] Different habitats result from variation in geological attributes, landforms, and processes, and the non-living components of ecosystems influence microclimates, control hydrology, facilitate nutrient cycling, and create niche space.[14,25,26] Areas of high geodiversity are therefore assumed to harbour high levels of biodiversity; this assumption forms the basis of the conservation strategy known as Conserving Nature's Stage.[22] This strategy suggests that instead of focusing on individual species or habitats (or occupants of the abiotic stage or arena), conservation actions should be targeted at landscapes or enduring geofeatures, which are capable of supporting high biodiversity under global change.[14,27] Targeting nature protection in the abiotic setting or in specific geofeatures (eg, individual landforms, soil types, rock types, and hydrological features) can result in valuable biodiversity advances[20,21] by conserving not only the known biodiversity but also that of which we are currently unaware, as well as the habitat for potential future species.

Geodiversity contributes to a wide range of geosystem services (also referred to as abiotic ecosystem services by the Common International Classification of Ecosystem Services), which are the benefits people gain from living and non-living nature.[15,28] Geodiversity underpins and maintains the delivery of both direct and indirect geosystem services.[29] Direct geosystem services include goods produced through surface and subsurface materials and processes, such as drinking water, sand deposits, and minerals. Specific geofeatures, such as water, also dilute and transport pollutants in ecosystems. In addition, interactions between non-living and living elements of nature yield direct geosystem services.[15] An example of this is a stream habitat for fish, in which, for example, differences in sediments, flow velocity, water-level fluctuation, depth gradient, and streambed profile create variable abiotic conditions for freshwater organisms to exist. Various cultural geosystem services are also a direct product of these materials and processes. For example, diverse landscapes provide opportunities for recreation and for educational and spiritual experiences.[16] Mining provides minerals and rock materials that are essential to human societies, as well as access to fossils—all of which contribute to the advancement of geosciences and are therefore of educational and scientific value to people.

Geodiversity further sustains ecosystems by providing regulating and maintenance services that are strongly associated with biodiversity. These indirect geosystem services generally consist of the transportation of biochemical or physical inputs to ecosystems, such as water, nutrient, and gas cycles. As such, geosystem services are widely associated with, for example, economic development, climate change adaptation, sustainable management of land and water, historical and cultural heritage, and human health and wellbeing.[11,13,15,17,30,31]

Although geodiversity is presumed to be more stable than biodiversity over time, it is also subject to changes or damage caused by human activities around the world.[26,28,32–34] For example, waters are increasingly polluted and degraded,[35,36] the mining of geological deposits—although essential for modern societies—is ravaging local geodiversity,[34,37] and infrastructure and building development threatens local natural landscapes.[29] The timescale for many elements of

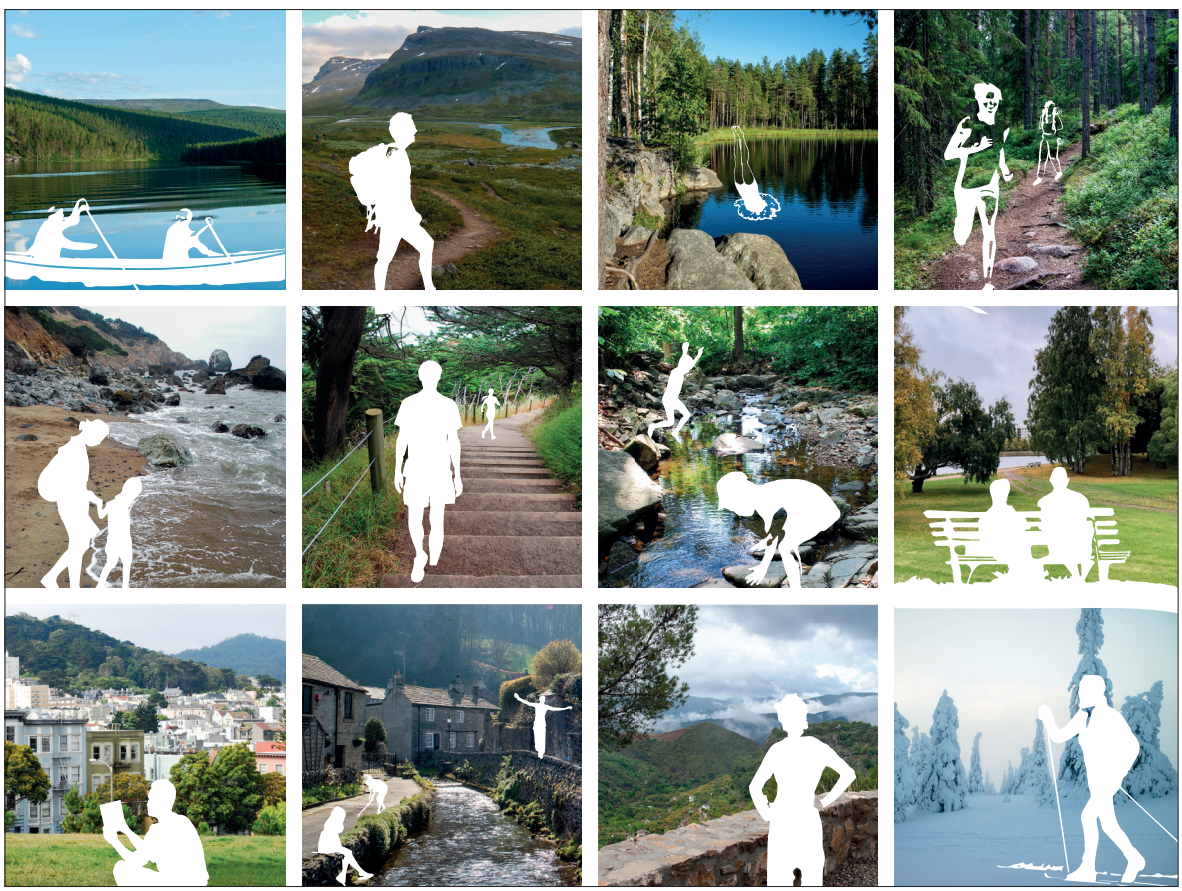

Figure 2: **Examples of how geodiversity potentially contributes to human health by providing green, blue, and white spaces and aesthetic experiences; promoting physical activity, mental health, and microbial contact; and facilitating a diverse environment for everyday life and activities**

geodiversity to recover from widespread deterioration can be millions of years.[13] As such, there is an urgent need for the sustainable use of geological deposits and landscapes, which requires the consideration of geodiversity alongside biodiversity when managing and restoring nature.[31,38,39]

Relationships between geodiversity, biodiversity, and human health

Evidence regarding the importance of biodiversity for human health and wellbeing is steadily accumulating. Biodiversity and greenness contribute to physical, mental, and social health and wellbeing through various pathways (figure 1).[6,7,9,39] First, contact with biodiversity is positively associated with physical health, for example, through enriching the human microbiome; promoting immune balance; lowering blood pressure; reducing the risk of obesity and diabetes; improving birth outcomes, child development, and pain control; facilitating recovery from injuries, birthing, and congestive heart failure; and protecting against inflammatory disorders.[6,39–43] Correlations between improved general health and contact with biotic nature have been suggested for both children and adults.[6,44] Second, biodiversity improves the mental health and wellbeing of people through reductions in stress, depression, aggression, and psychiatric disorders; better sleep; increased prosocial behaviour and social connectedness; and greater happiness and life satisfaction.[4,6,7,45,46] Finally, biodiversity supports physical health indirectly by improving air quality, alleviating the harmful effects of pollution, regulating heat and humidity, and reducing noise.[7,47,48] However, negative associations between vegetation and physical health are also evidenced, such as the worsening of asthma due to pollen, soil fungi, and other allergens.[6,41] Nonetheless, one of the best-known benefits of biodiversity for both physical health and mental health and wellbeing is the link between the natural environment and increased physical activity.[12,39,49–51]

Although biodiversity fosters human health and wellbeing in multiple ways, many of the positive health effects of nature arise from the non-living components that underlie biodiversity (figure 2). For example, contact with diverse microbes and other antigens could be reduced if geodiversity does not sustain high biodiversity above and below ground.[13,26] Different green spaces (ie, areas covered by vegetation, such as urban parks, playing fields, and forests) can only flourish if non-living

	Research priorities
Direct benefits	
Specific landforms and soils (eg, eskers with sandy soils) provide clean drinking water that supports physical health	These geofeatures should be better recognised globally and more conservation efforts are needed to protect the crucial geodiversity hotspots of physical health
Scenic landscapes (eg, mountain areas) and open-water sites promote mental health and wellbeing	The contribution of specific geofeatures and overall geodiversity to human health and wellbeing needs to be better understood in sociodemographically diverse populations
Geodiversity provides a wide range of natural features that can be used for diverse physical activities, which could offer myriad health benefits	We need to identify these natural features so that they can be utilised to support physical activity and human health; context-dependency concerning different populations, age groups, genders, cultures, and ethnic groups should be considered
Geodiversity is associated with human health through the built environment, in which infrastructure can be constructed to support the coexistence of high geodiversity and people	Land-use planning should support geodiverse areas to minimise geodiversity loss during building and construction and to encourage people to spend time in geodiverse areas in a sustainable way
Indirect benefits	
Geodiversity mitigates, regulates, and modifies the quality of nature	Identification and quantification of the different pathways through which geodiversity influences the quality of nature and improves human health; a crucial first step is to map geodiversity across scales, ecosystems, and countries using standardised measures, as such harmonised data are currently absent
Geodiversity supports diverse microbial and other antigen contacts above and below ground	Hygiene hypothesis is one of the likely mechanisms through which nature enhances the immune system;[6,40,41] this hypothesis should be tested within the context of geodiversity (ie, do high geodiversity sites have more microbial and antigen activity?)
Geodiversity provides essential light, moisture, and nutrients to green spaces (eg, parks and nature reserves), which promote physical, psychological, cognitive, and social health and wellbeing; as such, geodiversity and biodiversity mechanistically interlink non-living and living nature to support planetary health	Additional empirical evidence is needed to understand the relationship between geodiversity and biodiversity across spatial and temporal scales, regions, ecosystems, and biomes;[24] similar measures to account for different aspects of diversity (ie, diversity within and between places or regions) should be applied to maintain comparability in both geodiversity and biodiversity research
High geodiversity contributes to high biodiversity, supporting the Conserving Nature's Stage strategy	Although the theoretical foundations for the Conserving Nature's Stage strategy are strong, empirical evidence regarding the capability of high-geodiversity environments to maintain biodiversity over time is urgently needed

Table: **Potential benefits of geodiversity for human and planetary health and the agenda for research and action to capitalise on these benefits**

nature provides enough light, moisture, and nutrients through different geofeatures.[15,16,23] Both independently and together with biodiversity, geodiversity also further influences the quality of nature and affects human health and wellbeing. For example, increasing evidence shows that different water systems (known as blue spaces) mitigate temperature increases, provide beneficial aerosolised toxins and increase vitamin D synthesis.[11] Other geofeatures, such as different landforms of eskers and mountains, regulate and mitigate extreme conditions in nature by influencing the magnitude and direction of winds; temperature and solar irradiance; the concentration of oxygen, carbon dioxide, and other gases; and humidity.

The filtration of clean drinking water through soil and specific landforms, such as eskers, is one of the key mechanisms through which geodiversity directly affects physical health.[15] Another important such mechanism is through increased physical activity, which supports both physical health and mental health and wellbeing. Studies have shown that people are more likely to maintain physical activity in places with highly geodiverse landscapes.[11,12,52] Landscape characteristics, such as the richness of natural elements and aesthetically appealing landscapes, foster human health.[52,53] Additional benefits are likely to arise from improved mental health and enhanced immune systems when spending time in nature with high geodiversity.[11] Spending time in topographically varied areas or close to bodies of water is pleasing in terms of our aesthetic and sensory experience.[11,51,54] Perceived restoration of mental health has also been found to be positively associated with actual and perceived landscape heterogeneity,[55] which might also encourage repeated activities in environments with varied geodiversity and biodiversity. Although physical activity has been investigated as a mediator that links nature to mental health,[56] to our knowledge no studies have investigated physical activity as a mediator of relationships between biodiversity, geodiversity, and human health.

Future research and actions for preserving human and planetary health

The COVID-19 pandemic has taught us a serious lesson: human health is highly dependent on a viable nature.[57] Global change is causing severe biodiversity loss, which in turn threatens ecosystem functionality and the production of ecosystem services. Scientific statements published in the 2020s have called for a stronger coupling of climate change and biodiversity loss to tackle the deterioration of nature.[58,59] We support these statements and further emphasise that geodiversity should also be acknowledged in this framework. Many human actions—such as water pollution,[36] the mining of geological deposits to provide essential minerals and other materials (such as sand) to people,[37] and infrastructure and building development[29]—have resulted in the worldwide degradation of geodiversity.[31] Biodiversity and geodiversity are inherently interlinked, and living nature cannot prosper without its non-living counterpart.[13,60] Neither can we ignore the role of geodiversity in promoting human health.

Despite the existing research on specific elements of abiotic nature (such as blue spaces), or the links between geodiversity and biodiversity and ecosystem and geosystem services, much of the potential that geodiversity can offer to human health is yet to be revealed (table). Loss of biodiversity has been considered in many international agendas and agreements,[59] whereas loss of geodiversity was not widely acknowledged until 2020.[61] Considering geodiversity in current conservation efforts alongside biodiversity could help to maximise the agenda of environmental protection.[18] For example, UNESCO

has recognised the importance of geodiversity through three main mechanisms: International Geodiversity Day (Oct 6; first held in 2022); the World Heritage Convention; and the Global Geoparks Network, which is based on a holistic concept of geodiversity, nature conservation, education, and sustainable development. These are encouraging examples of considering abiotic nature as a source of human health and wellbeing, and a driver for sustainable economic and social development.

Safeguarding the diversity of nature can also be implemented in land-use planning and urban design. Areas with high geodiversity and biodiversity, or areas that include a variety of natural elements—such as green spaces, white spaces (areas covered with snow and ice),[62] and blue spaces—should be recognised and included when decisions on a healthy environment and sustainable future are being made. However, the implementation of sustainable planning is not easy, because our increasing demand for natural resources undermines biodiversity and geodiversity by fragmenting open and natural areas; deteriorating the quality and quantity of water resources; altering habitats, species communities, and landforms; and decreasing topographical variation of landscapes.[13,63] To promote biodiversity-friendly and geodiversity-friendly planning actions, decision makers and planners need to consider these potential synergies between nature and human health and wellbeing. Meanwhile, we need to raise public awareness of geodiversity and its supportive role for biodiversity and human health, so that communities can demand considerate and sustainable land use, urban planning, and business practices, and hold elected officials accountable.

To conclude, we argue that human and planetary health are intricately linked, and that human life strongly depends on a viable nature. For many years, biodiversity was considered almost synonymous with nature, neglecting the role of geodiversity as the underlying force of living nature. Geodiversity affects human health and wellbeing directly and indirectly through biodiversity. Geodiversity is a poorly understood area with untapped potential to ensure essential ecosystem functionality and good living conditions for people in a time of changing environments.

Contributors

JA led the writing of the manuscript, with major contributions from HT, RK, and DD. MT was responsible for the figures. All authors critically revised the work, approved the final version, and agreed to be accountable for all aspects of the work.

Declaration of interests

We declare no competing interests.

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