To advance sustainable stewardship, we must document not only biodiversity but geodiversity

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Rapid environmental change is driving the need for complex and comprehensive scientific information that supports policies aimed at managing natural resources through international treaties, platforms, and networks. One successful approach for delivering such information has been the development of essential variables for climate (1), oceans (2), biodiversity (3), and sustainable development goals (4) (ECVs, EOVs, EBVs, and ESDGVs, respectively). These efforts have improved consensus on terminology and identified essential sets of measurements for characterizing and monitoring changes on our planet. In doing so, they have advanced science and informed policy. As an important but largely unanticipated consequence, conceptualizing these variables has also given rise to discussions regarding data discovery, data access, and governance of research infrastructures. Such discussions are vital to ensure effective storage, distribution, and use of data among management agencies, researchers, and policymakers (5, 6).

Mining is one example of the human impact on geodiversity. Active mines cause a decrease in local biodiversity, but in some cases they can provide an important habitat for specialized and rare species after the mine has been abandoned. Image credit: Shutterstock/1968.

Although the current essential variables frameworks account for the biosphere, atmosphere, and some aspects of the hydrosphere (1–4), they largely overlook geodiversity—the variety of abiotic features and processes of the land surface and subsurface (7). Analogous to biodiversity, geodiversity is important for the maintenance of ecosystem functioning and services (8), and areas high in geodiversity have been

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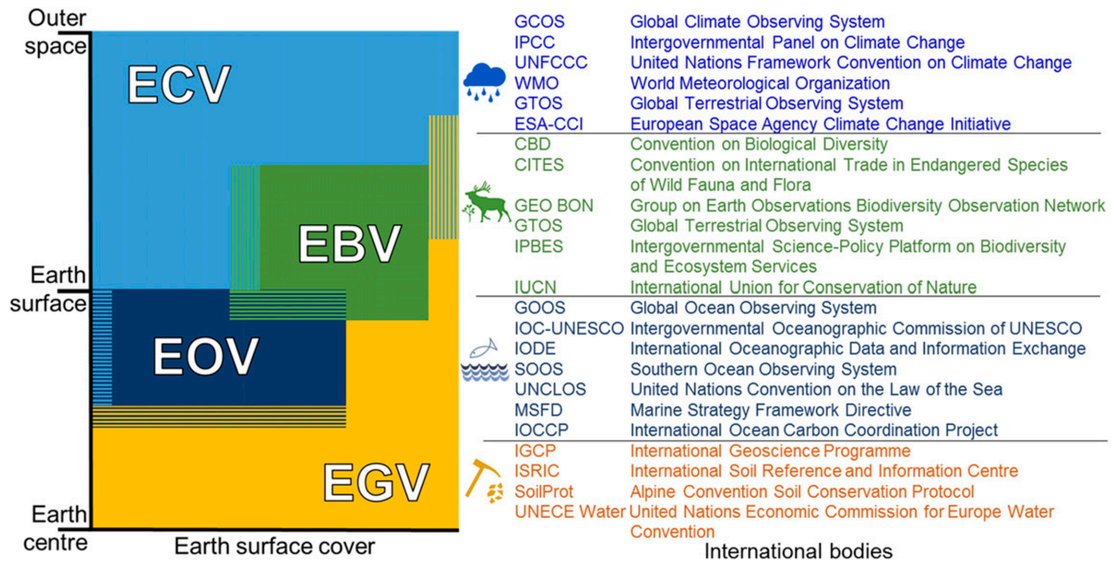

Fig. 1. Schematic proportions of the Earth covered by existing EBVs (green), ECVs (light blue), and EOVs (dark blue) and by our proposed EGVs (orange). Although life occurs throughout the ocean environment, EOVs refer predominately to abiotic aspects such as ocean physics and biogeochemistry, which do not overlap with EBVs (by definition exclusively covering biotic aspects). Consequently, the EBV box does not extend across the whole Earth surface (horizontal axis). Some essential variables do overlap, as indicated by the striped sections, for example, zooplankton diversity is both an EBV and EOV, whereas surface water is both an ECV and EGV. Several major international conventions (right) monitor and assess networks associated with each essential variable concept.

shown to support high biodiversity (9). Thus, consideration of geodiversity is an important part of developing nature-based solutions to global environmental challenges and demands for natural resources, particularly in relation to human well-being and ecosystem functioning.

And yet, despite many facets of sustainable development being underpinned by access to geological assets, key elements of geodiversity are yet to be incorporated into policy documents and international conventions. We, therefore, propose essential geodiversity variables (EGVs) describing features and processes of Earth's abiotic surface and subsurface to advance science and sustainable stewardship, complementing the existing essential variables (Table S2). These EGVs will enable more holistic and better-informed monitoring efforts, decision making, and responses to global change.

Broad Scope

The scope of geodiversity covers a wide range of policy areas, including terrestrial and marine conservation, sustainable use of natural resources, public health, natural hazard management, recreation, and tourism [e.g., see the "Conserving Nature's Stage" (10) and geosystem services (11) concepts]. For example, abiotic features, including geothermal springs, inspired the creation of the world's first national park, Yellowstone National Park. This park aimed specifically to safeguard geodiversity, and a century later its geothermal springs were the discovery site for *Thermus aquaticus*, a bacterium containing a thermostable enzyme that is used to amplify DNA segments and is, thus, the foundation of modern gene technology.

Another illustration of the critical importance of understanding and monitoring geodiversity globally concerns resource extraction. Removal of natural resources can decrease geological or mineral diversity, negatively impact local ecosystems (because of toxic extraction methods), and conflict with human rights. Notably, mobile phones with touch screens contain 54 elements of the periodic table, many of which are unevenly distributed in nature around the world and, thus, represent resource security concerns. Continued resource extraction is essential for achieving the sustainable development goals (SDGs), but trade-offs with biodiversity conservation and human rights need to be explicitly addressed. For example, the transition to renewable energy sources will require the extraction of new minerals (e.g., materials for solar panels), as will greater urbanization and fertilizers for enhanced food security (12). Some tools and concepts necessary for incorporating such trade-offs are already available but not commonly applied within the context of the SDGs, for example, in the form of the geosystem services approach (11).

And although some EGVs, such as groundwater, are already considered within international legislation (e.g., the European Union Groundwater Directive), most are underrepresented or not effective over wider regions. For example, currently the only binding international convention specifically for soil conservation is the 1991 Alpine Convention's Soil Conservation Protocol (13), which omits most of the Earth's surface. Similarly, extraction of sand—a key ingredient in building materials and electronics—remains largely unregulated, despite rising global demand for this finite resource and wide-ranging, devastating environmental consequences resulting from its extraction (14). The demand for minerals is rising globally, yet their extraction lacks international governance (15).

Meanwhile, extraction and storage of vast quantities of soil and rock that are byproducts from mining metals, as well as associated land requirements, are currently not part of integrated broad-scale management frameworks (16).

Essential Variables

In presenting the EGV concept, we aim to 1) complement and augment existing essential variables (ECVs, EOVs, EBVs, and ESDGVs) (Fig. 1), 2) improve global coordination of monitoring strategies, and 3) advance communication between policymakers and geoscientists. To achieve these goals, we propose a framework for policymakers and researchers to guide future definitions of relevant measurements that capture the key elements of geodiversity. We define EGVs as abiotic state and process variables related to geology, geomorphology, soils, and hydrology 1) relevant to natural resource management and human well-being, conservation, or ecology; 2) complementary to (and not duplicating) the other suites of essential variables; and 3) feasible and cost effective to measure (Fig. 1). In Table S2, we propose a candidate set of variables.

Some aspects of EGVs are already used by international conservation organizations; these provide a solid basis for further integrating EGVs into global treaties and international conventions. For example, the International Union for Conservation of Nature (IUCN) refers to the relevance of geodiversity for the conservation of natural resources within three resolutions titled "Conservation of Geodiversity and Geological Heritage," "Valuing and Conserving Geoheritage Within the IUCN Programme," and "Conservation of Moveable Geological Heritage." Furthermore, the United Nations Educational, Scientific and Cultural Organization recognizes the outstanding universal value of geodiversity elements with their inclusion in both the World Heritage List (in May 2019, 95 properties in 53 countries worldwide) and in the Global Geoparks Network (140 Geoparks in 40 countries, as of May 2019). Many protected areas have the preservation of geodiversity and geoheritage as a goal of their management planning, including the Spanish network of Biosphere Reserves, Australia's New South Wales National Parks, and the US National Park Service. Meanwhile, the Food and Agriculture Organization coordinates a Global Soil Partnership that seeks to monitor the state of global soils and improve the governance and effectiveness of soil information.

Data and information products to measure changes in EGVs at management-relevant timescales are increasingly available and sometimes linked to global observatories, such as the Global Earth Observation System of Systems, with its Societal Benefit Areas (SBAs). However, these mainly cover natural hazards such as floods, earthquakes, and landslides (e.g., SBA disaster resilience). Where dangers are more diffuse or related to natural resource use, EGVs are not yet available (e.g., relating to global sand extraction and domestication of soil resources).

Making EGVs Work

Overall, despite the clear global importance of geodiversity, very limited international efforts have been devoted to developing measures that support decision making for supranational and global policy targets and SDGs [although there have been efforts to do so in the past (17)]. Geodiversity is highly relevant, for example, to the IUCN World Parks Congress, the World Conservation Congress, the Convention on Biological Diversity's Aichi targets, SDGs, and the Sendai Framework for Disaster Risk Reduction (Table S2). In Table S1, we specifically link EGVs to the 17 SDGs and four Sendai Framework priorities.

We advocate a holistic approach that recognizes and tracks the integrity of the abiotic and biotic components of geosystems and ecosystems as the most effective means to address global environmental challenges. Following the examples of the ECV, EOV, and EBV communities, we recommend collaborative development of comprehensive and interoperable databases of geodiversity globally, following common protocols, a standardized terminology (e.g., controlled vocabularies), and a consistent metadata reporting. We further recommend forming an expert panel, for example within the Group on Earth Observation framework, to further develop the conceptual framework of EGVs. Finally, we encourage better communication with policymakers about the importance of considering EGVs in international conventions and policy documents. This could be enhanced by applying a "geosystem services" concept, which would complement the successful ecosystem services concept whose use within a policy and international treaties context was advanced by the Millennium Ecosystem Assessment (11). Better communication would also be enhanced by applying the recently published International Panel on Climate Change communication recommendations.

Attaining a sustainable circular economy and safeguarding our natural resources, while also accounting for population growth, further urbanization, and improved well-being, will require international consideration of material flows and their impacts across terrestrial and aquatic systems globally.

We now have the technical capacity and experience from other scientific communities to describe abiotic characteristics of Earth's surface and subsurface and to develop holistic and parsimonious measures of geosystem and ecosystem structure, function, and risks. Attaining a sustainable circular economy and safeguarding our natural resources, while also accounting for population growth, further urbanization, and improved well-being, will require international consideration of material flows and their impacts across terrestrial and aquatic systems globally. This will entrench a more holistic approach to nature, improving our efforts to designate protected areas and enhance the management of natural resources. Doing so is essential for safeguarding biodiversity, geodiversity, ecosystem, and geosystem services in a rapidly changing world and for integrating and balancing the economic, social, and environmental dimensions of sustainable development.

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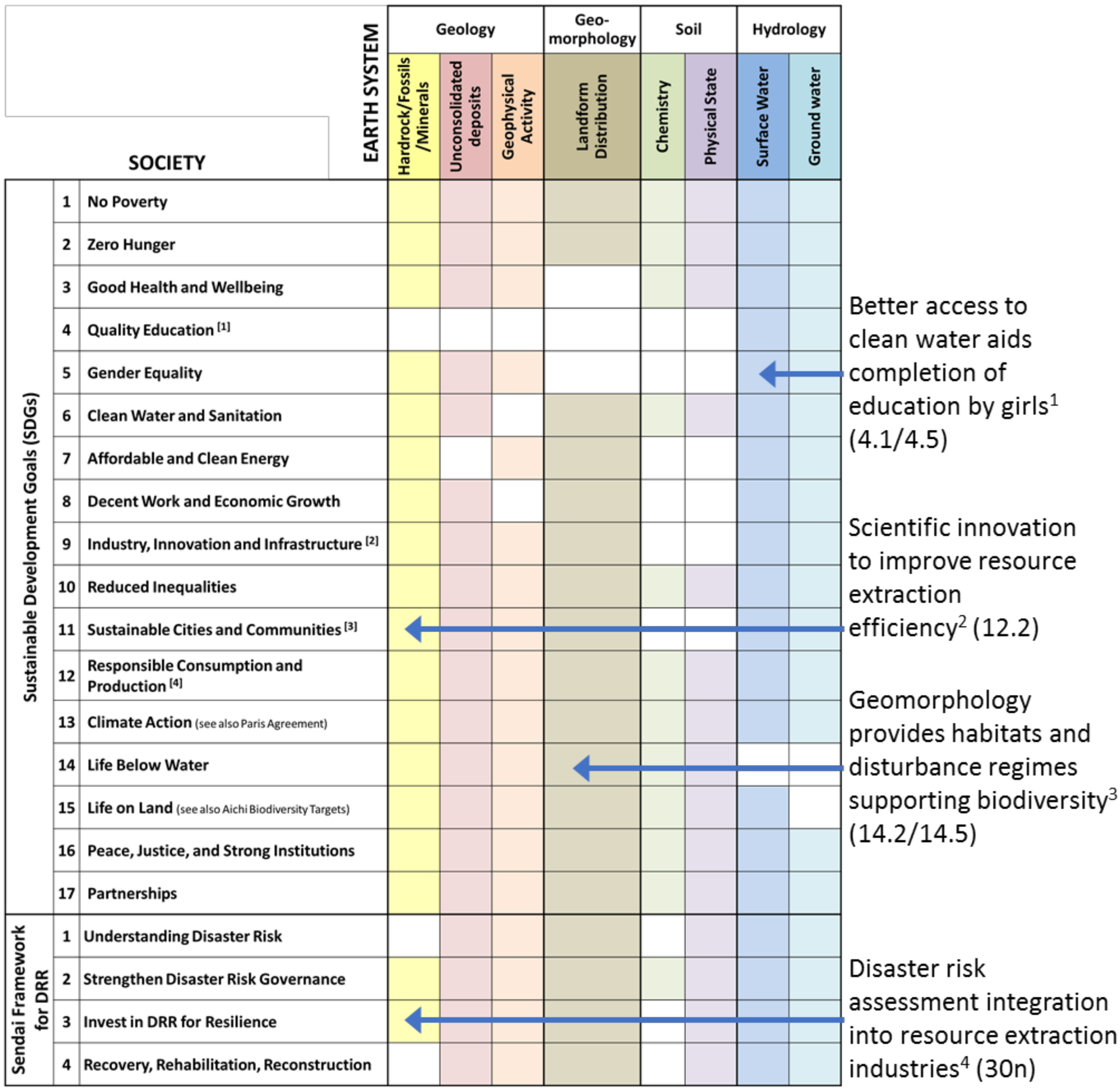
Supplementary Materials

Table 1 How geodiversity and Essential Geodiversity Variables (EGVs) can help implement and monitor the UN Sustainable Development Goals and the Sendai Framework for Disaster Risk Reduction Priorities for Action



Examples are given to the right of the table. Raising awareness of the role of all the EGVs in sustainable development is needed to achieve SDGs Targets 4.7. and 12.8. Enhanced scientific research on all the EGVs, and strengthened capacity in the Global south, are needed to achieve

SDGs Target 9.5.

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Table 2 Non-exhaustive list of proposed Essential Geodiversity Variables (EGVs), their definition, examples, and policy relevance.

EGV class	EGV	Definition	Examples	Policy relevance
Geology	Hardrock, fossil & mineral distribution	Geological materials and their spatial distribution	- Natural resources (e.g. coal, gas, ore)	- Economy - Geo/nature conservation - Environmental impact assessment - Pollution management
	Un-consolidated Deposits	Surface distribution of parent materials resulting from geomorphological processes	- Distribution / scarcity of materials (e.g. sand) - Dynamics of surface materials (e.g. sedimentation)	- Economic values of resources - Coastal defence - Combatting erosion - Hazard/risk assessment - Land use planning
	Geophysical processes	Variability of the intensity of geophysical processes	- Earthquakes - Volcanic eruptions - Earth radioactivity - Thermal energy - Land subsidence	- Early warning systems - Hazard mitigation - Hazard/risk assessment - Building regulations - Nature conservation

Geo-morphology	Landform distribution	Landforms and their spatial distribution	- Distribution of landforms resulting from erosion, transport, sedimentation - Dynamics of geo-hazards	- Hazard/risk assessment - Combatting erosion - Conservation - Evacuation plans - Flood regulation
Soil	Chemistry	Distribution and quantity of chemicals in the pedosphere	- Fertility - Soil salinization - Pollutants - Minerals	- Sustainable soil use directives - Pollution, environmental impact assessment - Agriculture
	Physical state	Distribution and quality of soil structure and texture	- Formation and degradation of soils - Soil erosion	- Soil conservation - Combatting desertification - Agriculture
Hydrology	Surface water	Distribution, permanence and quality of surface water and ice	- River dynamics - Drinking water quality / irrigation water volume - Dam construction	- Flood risk management - Irrigation planning - River training (dikes) - Sustainable water policies - Energy generation
	Ground water	Subsurface (ground) water resources	- Aquifer size and quality	- Sustainable groundwater policies - Land use planning - Groundwater rise - Agriculture - Drainage