Remote Sensing of Geomorphodiversity Linked to Biodiversity

Subjects: Remote Sensing | Geology | Others

Contributor: Angela Lausch , Michael E. Schaepman , Andrew Skidmore , , Olaf Bastian , Erik Borg , Jan Bumberger , Peter Dietrich , Cornelia Glaesser , Jorg Hacker , Thomas Jagdhuber , András Jung , Arnon Karnieli , Reinhard Klenke , Uta Ködel , Wolfgang Kresse , Ulf Mallast , Carsten Montzka , Markus Möller , Hannes Mollenhauer , Md Minhaz Rahman Talukder , Christiane Schmullius , Peter Selsam , Dr. Ralf-Uwe Syrbe , Sina Christine Truckenbrodt , Michael Vohland , Martin Volk , Thilo Wellmann , Steffen Zacharias

Remote sensing (RS) enables a cost-effective, extensive, continuous and standardized monitoring of traits and trait variations of geomorphology and its processes, from the local to the continental scale. RS technologies can record geomorphic traits, their diversity and variations, from which the other four geomorphodiversity characteristics are derived. However, compared to in situ measurements, RS approaches can only record certain parts of these geomorphic traits and their variations. This is because capturing geomorphic traits and diversity using RS approaches is limited by various constraints, namely: (1) the characteristics and spatial-temporal distribution of geomorphic traits; (2) the characteristics of geomorphological processes; as well as (3) the RS sensor characteristics, the chosen RS platforms and the characteristics of RS data-processing and classification information. These constraints and limitations define the detectability, feasibility, accuracy, depth of information, repeatability, and, thus, standards disability in monitoring the five geomorphic characteristics using RS approaches.

Remote sensing Geomorphodiversity Structural Taxonomic Genesis Functional Traits Geomorphic Traits Biodiversity Earth Observation

1. Characteristics of Geomorphodiversity

Geomorphodiversity, as part of geodiversity, can be described by its five characteristics, namely: (a) geomorphic trait diversity, (b) geomorphic genesis diversity, (c) geomorphic structural diversity, (d) geomorphic taxonomic diversity, and (e) geomorphic functional diversity . These five characteristics of geomorphodiversity exist on all spatial, temporal, and directional scales of geomorphic organization and interact and influence each other, as well as affecting biodiversity and further spheres of geodiversity such as the lithosphere, hydrosphere, or atmosphere, either directly or indirectly on all these scales. The five characteristics of geomorphodiversity are defined by Lausch et al. [1] as:

- Geomorphic trait diversity, which represents the diversity of mineralogical, bio-/geochemical, bio-/geo-optical, chemical, physical, morphological, structural, textural, or functional characteristics of geomorphic components that affect, interact with, or are influenced by geomorphic genesis diversity, geomorphic taxonomic diversity, geomorphic structural diversity, and geomorphic functional diversity.

- Geomorphic genesis diversity represents the diversity of the length of evolutionary pathways, linked to a given set of geomorphic traits, taxa, structures, and functions. Therefore, sets of geomorphic traits, taxa, structures, and functions are identified that maximize the accumulation of geomorphic-functional diversity.

- Geomorphic structural diversity, which is the diversity of composition and configuration of 2D to 4D geomorphic structural traits.

- Geomorphic taxonomic diversity, which stands for the diversity of geomorphic components that differ from a taxonomic perspective.

- Geomorphic functional diversity, which is the diversity of geomorphic functions and processes, as well as their intra- and interspecific interactions.

A clear separation and assignment of the five characteristics of geomorphodiversity is not always possible, but nevertheless helps to monitor, assign and assess the various indicators of in situ and RS approaches, as well as to understand the links between both approaches.

Geomorphic traits that can be monitored using RS techniques in various regions of the electromagnetic spectrum are called spectral traits (ST); the changes to these spectral
Remote Sens. 2022, 14, 2279 10 of 48 traits are referred as spectral trait variations (STV). Hence, the respective RS approaches are referred as RS spectral traits and RS spectral trait variations—concept (RS-ST/STV-C; see **Figure 1**) [2].

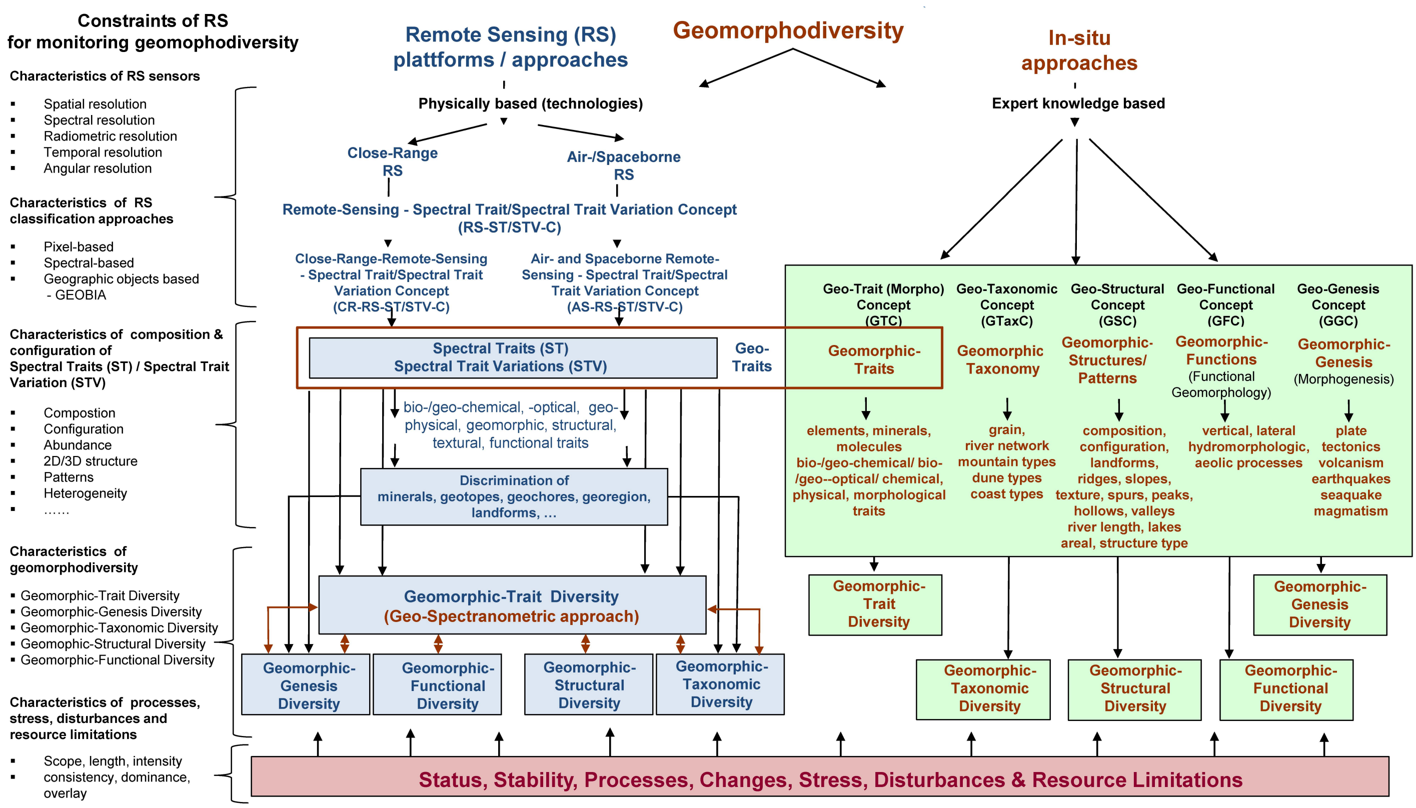

Figure 1. In situ and remote sensing (RS) approaches, common links, and the constraints of RS for monitoring the five characteristics of geomorphodiversity. Geomorphological traits are the crucial link between in situ and RS monitoring approaches (from Lausch et al. [1]).

2. Geomorphic Trait Diversity and Its Changes Using RS

"Geomorphic trait diversity represents the diversity of mineralogical, bio-/geochemical, bio-/geo-optical, chemical, physical, morphological, structural, textural or functional characteristics of geomorphic components that affect, interact with or are influenced by the geomorphic-genesis diversity, the geomorphic taxonomic diversity, the geomorphic structural diversity, and the geomorphic functional diversity" .

Only when features, such as the radiometric, geometric, spectral, angular, or temporal resolution of RS sensors, are specific for the detection of geomorphological spectral features, these can be detected with RS. The requirements for the resolutions differ, for example, when different minerals (silicates, oxides, carbonates, sulfates, chlorides), material types (sand, rock, gravel, soils), material properties (texture, colors, shapes) or form features (river valleys, fracture steps, pits, slope inclinations, or curvatures of river loops) should be detected.

RS can record and monitor geomorphic trait diversity based on geomorphic spectral traits/trait variations. If the landforms to be recorded do not differ with respect to the mineralogical, bio-/geochemical, bio-/geo-optical, chemical, physical, morphological, structural, textural, or functional characteristics of their geomorphic components, then they cannot be differentiated from each other using RS technologies. The detectability of geomorphic trait diversity forms a crucial basis for the detection, differentiation, classification, and monitoring of the remaining four characteristics of geomorphodiversity.

In regions without vegetation cover compared to regions with vegetation cover, the recording of geomorphic trait diversity with RS technologies is possible using direct RS indicators. The spectral RS signal is the result or integral of the state and the changes, shifts and/or disturbances of geomorphic traits, geogenesis traits, structure traits, and taxonomy as well as functional traits. In regions covered by vegetation, water or ice, indirect indicators may be used in addition to the direct RS indicators that are integral to the response of traits in bacteria, algae, plants, populations, communities, and traits of landforms and their interactions.

RS techniques are, therefore, the only and the most essential method and basis for monitoring geomorphic trait diversity, which is the basis of the geo-spectranometric approach and the "spectral fingerprint of geomorphology and geomorphodiversity".

3. Geomorphic Genesis Diversity Using RS

"Geomorphic genesis diversity represents the diversity of the length of evolutionary pathways, linked to a given set of geomorphic traits, taxa, structures, and functions. Therefore, sets of geomorphic traits, taxa, structures and functions that maximize the accumulation of geomorphic functional diversity are identified".

The Siberian Trap and the Deccan Trap, also called the Deccan Large Igneous Province, are examples of geological volcanic eruptions that led to the formation of characteristic geomorphic genesis diversity [7]. As a result of the volcanic activity from 252 million years ago (the duration of the flood basalt event being ~900,000 years), extensive areas of flood basalt (with a total thickness of up to 6500 m) were formed in the Siberian Traps. The Sibierian Traps extend from the West and North Siberian Lowlands and the Central Siberian Highlands as well as to part of the Central Yakutian Lowlands, including the western slope of the East Siberian Highlands. The impacts of the eruptions produced up to ~2000 km^3 of lava, leading to a large-scale distribution and volcanic deposit-covered area of ~7 million km^2. Enormous releases of sulfur dioxide, methane, carbon dioxide, and large amounts of hydrogen sulfide from volcanic as well as organic (bacterial) sources [8], resulting in the formation of mountain structures such as the Putorana Mountains. Present-day deposits of silicon-rich migmatites, large amounts of volcanic tuffs, and pyroclastic deposits such as rhyolite, and metal-bearing rocks such as nickel, copper, and palladium are mined from extensive deposits today. The eruptions and their impacts are thought to be causally related to the mass extinction at the end of the Permian era. Thus, the toxic effects and extreme temperature increase of terrestrial and marine areas by 8 to 10 °C led to the collapse of many ecosystems and the emergence of new forest habitats, which only repopulated larger areas after about 15 million years. In contrast to the ammonites, conodonts, and foraminifera (with a regeneration time of 1 to 3 million years), the damaged coral reefs needed some 8 to 10 million years for complete regeneration.

RS has added a new dimension to the monitoring of geomorphic genesis diversity, its characteristics, consequences, disturbances, and biodiversity. RS can describe genesis traits (minerals, rock types), taxa (mountain types) structures (genesis patterns, lineaments), and functions (run-off behavior), which represent geological tectonic architecture and its features [9]. Detailed structural and pattern analyses using RS technologies help to interpret, classify, discriminate and, thus, identify the genesis of various structures and patterns in the

Siberian and Deccan Traps [7]. Thus, RS-based lineament analyses are crucial key elements for interpreting local, regional, and continental geogenetic structures [10]. Any naturally formed linear feature on the Earth's surface that is related by the processes of extension, compression, strike-slip, or as a result of the magmatic or metamorphic activity, is called a lineament [7]. There are various geotaxonomic forms of lineaments, including rock types, linear sinkholes, fault-related traps, fold hinges, faults, shear zones, dykes, mineralized veins, uplifted topography, or contacts between elongated fractures or fault-bound elongated valleys [10][11]. In addition to lineaments, terrain patterns or fluvial drainage patterns provide important clues about the causes, trends, and nature of subsurface structures that cannot be detected with RS [10]. Drainage patterns in flat terrain are usually dendritic; however, in a dome or mountain structure, drainage patterns are radial and concentric [6]. Orthogonal, barbed, and double-drainage or compressed meanders are other examples of drainage patterns that control the course of water movement through their structure [7][10][12].

If lineaments, their patterns, or substructures are not directly visible and cannot be recorded using RS techniques, then, vegetation traits or plant functional types [12][13] or land-use anomalies and groundwater patterns [14], or the delineation of shallow Deccan basaltic aquifers using aerial photointerpretation [15], or channel widths, landslides, faults, or high-spatial-resolution Google Earth imagery in the study of Earth surface processes [16] can be used directly or as a proxy for geomorphic genesis diversity.

4. Geomorphic Structural Diversity Using RS

"Geomorphic structural diversity is the diversity of composition and configuration of 2D to 4D geomorphic structural traits" .

Exogenous and endogenous processes are responsible for generating relief and form, leading to the development, structuring, and shaping of Earth's crust and entire ecosystems. Geomorphometry, geomorphic structure, patterns, diversity, relief, and topography are all crucial for the functionality, feedback, and resilience of geomorphology and the biota controlling the Earth's surface processes and landforms [19][20][21]. Spatial-temporal heterogeneity and evolutionary geomorphological structures and patterns lead to plant and animal species diversity and gradients in ecosystems, increasing the niche dimensionality of species and consequently supporting species richness and biodiversity [22] [23]. The 2–3D structures and sculpture forms, patterns, and communities enable essential conclusions to be drawn about the relief, structure, rock, and soil-formation processes during genesis. The diversity of geomorphic structures, patterns, and forms provides not only crucial information about the type and origin of the process but also its characteristics, such as the scope, length, intensity, consistency, dominance, and overlay of the process. Further more, spatial-temporal geomorphic patterns can equally be used to describe the degree of naturalness or anthropogenic influence or degree of human influence (hemeroby) [24][25] on geomorphology and landforms.

Through land use intensity (LUI) and urbanization, ponst-mining landscapes, forestry intensification or river regulation evolutionary geomorphic structures and shape patterns are altered and, in some cases, are so heavily overprinted that the original evolutionary structures are now challenging to monitor. Numerous examples of geomorphic imprinting define the terrain of present-day cultural landscape, such as buildings, cities, streets, terraces, boundary walls, brownfields, ditches, canals, reservoirs, or restored wetlands. The characteristics of geomorphic structures are, therefore, crucial fingerprints of human influence [26]. For this reason, geomorphic structural diversity is an important indicator for measuring and assessing inferences regarding the state, changes, and the origin, type, and intensity of human influence. . Geomorphic structures and patterns are crucial for the discrimination of geomorphic taxa and, thus, the characterization of geomorphic taxonomic diversity using RS.

Structural diversity exists on all levels of a geomorphic organization. Therefore, structural geomorphic traits can be recorded by different RS platforms and, thus, on all spatial-temporal and directional scales of geomorphology. To successfully record and monitor structural diversity and its traits, the spatial, spectral, radiometric, angular, and temporal characteristics of the RS sensors play a significant role. Moreover, the distribution, density, and composition, as well as the configuration of structural traits, also play a major role here. Examples are the structures of fluvial landforms such as channel characteristics, floodplain morphology hydraulic channel morphology, geometries, topography, river width arc length, longitudinal transect or channel slope, or below waterline morphology. Morphometric patterns can be recorded with high-resolution LiDAR technologies, whereas optical RS approaches are doomed to fail with a spatial resolution of only 20 cm.

The choice of sensor technologies and characteristics is crucial to capture the exact geomorphological structure, such as topography. This will determine the model quality and, consequently, the quality of the prediction of disturbance effects in landscapes. Thus, ecological and hydrological model predictions are only as good as the quality of the input data that are collected by RS . For example, by capturing the detailed terrain structures of coastal regions through airborne LiDAR data, it has been demonstrated that more than three times as many people are at risk from climate change and rising sea levels than was previously calculated from less detailed shuttle radar topography (SRTM)-DEM-RS data [27].

5. Geomorphic Taxonomic Diversity Using RS

“Geomorphic taxonomic diversity is the diversity of geomorphic components that differ from a taxonomic perspective” .

Different evolutionary processes (geogenesis), such as plate tectonics, mountain building, or volcanism are described by the numerous geomorphic taxa (also referred to as types, classes, or units) of mountains, reliefs, volcanoes, channels, rocks, and landforms, leading to the development of different geomorphic taxa with specific geochemical, mineralogical, and structural properties, forms, and shape classes. This taxonomic diversity, heterogeneity, and richness of different geomorphic types (mountains, dunes, coast, or dune types) define the state, stability, and resilience of the entire geosphere and biosphere, as they induce a high diversity of ecosystem processes, functions, forms, and types of structures, ultimately forming ecological niches.

Different geomorphic types (taxa) vary in terms of their different geomorphic traits, in their geogenesis, structure, and function. For example, the production of volcanic lavas, solids, and gases shapes various characteristic volcanic forms. In addition, there are differentiating properties of the resulting volcanic products, such as gaseous, viscous, or low viscosity to solid properties. Likewise, the character of the production of different volcanoes differs, e.g., from explosive to effusive. Cinder volcanoes, for example, were formed from loose material and have a characteristic cone shape with a slope of 30–40°, leading to the formation of the distinctive concave slope shape. Furthermore, volcanic ash created the vast grass-covered savannah areas of the Serengeti, preventing the invasion and development of forest communities.

However, anthropogenic changes, such as land-use intensity, agricultural expansion, urbanization, climate change, or resource extraction have influenced, shaped, and defined a variety of landforms and geomorphic types for thousands of years [29]. This has led to changes in evolutionary types and the formation of distinctive anthropogenic-geomorphic types with strong anthropogenic features such as reservoirs, embankments, canals, mines, terraces or roads, buildings, and cities [26]. The expression of geomorphic characteristics and types present today, thus, range from “purely evolutionary types” to “strongly anthropogenic-geomorphic-dominated types”, which demands special recording and assessment procedures. Anthropogenic geomorphic features, such as linear structures, river straightening, and the characteristic structures of terraces or mines can now be used to monitor the degree of human influence and to improve the discrimination and classification of geomorphic types.

RS techniques can capture traits in geomorphology [1] , soil characteristics [2], and the responses of above- and belowground diversity [30] as well as biodiversity [14], depending on their RS characteristics. Many RS technologies are being used to detect human impacts and changes in the geomorphic taxa through LUI, using spectral image analysis—such as the monitoring of river degradation, terrain creation [26], and coastal structure changes with LiDAR [27] or urbanization (cities and roads) using multispectral, LiDAR or RADAR technologies [26].

6. Geomorphic Functional Diversity Using RS

“Geomorphic functional diversity is the diversity of geomorphic functions and processes as well as their intra- and inter-specific interactions” .

Through anthropogenic impacts, such as urbanization, land-use intensity, and river straightening, the 19th to the 21th centuries increasingly witnessed irreversible changes and disturbances to the natural geomorphology, leading to considerable disturbances in the functionality and resilience of geosystems.

Rivers adapt their path according to the temporal variations of their outflow. Hence, during geogenesis, meanders emerged due to convergent and divergent flow movements that were transverse to the general direction of flow. The number of factors influencing the formation of meanders can still not be fully explained today. However, it is understood that the meanders of a river are the expression of a stable, dynamic balance between the river and the riverbed, creating characteristic fluvial biodiversity with high self-purification potential. The geometry of meanders, both cut-off meanders and oxbows, can greatly differ since meanders are subject to a permanent positional change. In the 19th century, flood prevention measures were undertaken on the Upper Rhine (a reduction in areas prone to flooding), to regulate low-water levels (e.g., for year-round shipping) as well as regulations to produce hydropower.

The morphological impacts of these “corrective measures“ on the River Rhine in Germany altered the erosion and sediment behavior of the river. At the same time, the flow velocity increased, leading to strong vertical erosion of up to 7 m in the Rhine. As a result of this eroded material, sandbanks and gravel banks frequently formed, and these barrages acted as sediment traps, which meant that further measures were then required to regulate low-water levels [31]. Hence, river regulations or barrages lead to changes in the genesis, structural and functional fluvial traits, subsequently leading to fluvial trait variations. The structural geomorphological changes in the original meandering or sediment displacement can now be recorded using RS approaches because these fluvial trait variations lead to spectral responses in the RS signal. In addition to structural changes, hyperspectral technologies (HySPEX, AISA, CHIME, or EnMAP) can be used to make statements about changes to vegetation diversity and water quality (increasing eutrophication, chlorophyll content, and turbidity); in other words, impacts from river straightening. There are numerous examples of monitoring topography and relief (DEM, DSM) using RS technologies.

References

1. Lausch, A.; Schaepman, M.E.; Skidmore, A.K.; Truckenbrodt, S.C.; Hacker, J.M.; Baade, J.; Bannehr, L.; Borg, E.; Bumberger, J.; Dietrich, P.; et al. Linking the Remote Sensing of Geodiversity and Traits Relevant to Biodiversity—Part II: Geomorphology, Terrain and Surfaces. Remote Sens. 2020, 12, 3690. [CrossRef]
2. Lausch, A.; Baade, J.; Bannehr, L.; Borg, E.; Bumberger, J.; Chabrilliat, S.; Dietrich, P.; Gerighausen, H.; Glässer, C.; Hacker, J.; et al. Linking Remote Sensing and Geodiversity and Their Traits Relevant to Biodiversity—Part I: Soil Characteristics. Remote Sens. 2019, 11, 2356.
3. Clark, R.N.; Swayze, G.A.; Livo, K.E.; Kokaly, R.F.; Sutley, S.J.; Dalton, J.B.; McDougal, R.R.; Gent, C.A. Imaging spectroscopy: Earth and planetary remote sensing with the USGS Tetracorder and expert systems. J. Geophys. Res. Planets 2003, 108, 5.
4. Shumack, S.; Hesse, P.; Farebrother,W. Deep learning for dune pattern mapping with the AW3D30 global surface model. Earth Surf. Process. Landf. 2020, 45, 2417–2431.
5. Farmakis-Serebryakova, M.; Hurni, L. Comparison of Relief Shading Techniques Applied to Landforms. ISPRS Int. J. Geo.-Inf. 2020, 9, 253.
6. Ventura, G.; Vilardo, G.; Terranova, C.; Sessa, E.B. Tracking and evolution of complex active landslides by multi-temporal airborne LiDAR data: The Montaguto landslide (Southern Italy). Remote Sens. Environ. 2011, 115, 3237–3248.

7. Dasgupta, S.; Mukherjee, S. Remote Sensing in Lineament Identification: Examples from Western India. In Problems and Solutions in Structural Geology and Tectonics; Elsevier Inc.: Amsterdam, The Netherlands, 2019; Volume 5, pp. 205–221. ISBN 9780128140482
8. Dasgupta, S.; Mukherjee, S. Remote Sensing in Lineament Identification: Examples from Western India. In Problems and Solutions in Structural Geology and Tectonics; Elsevier Inc.: Amsterdam, The Netherlands, 2019; Volume 5, pp. 205–221. ISBN 9780128140482.
9. Mather, T.A.; Schmidt, A. Environmental Effects of Volcanic Volatile Fluxes from Subaerial Large Igneous Provinces, 1st ed.; GeophysicalMonograph 255; Ernst, R.E., Dickson, A.J., Bekker, A., Eds.; Wiley Online Library: Hoboken, NJ, USA, 2021; ISBN 9781119507444.
10. Dasgupta, S.; Mukherjee, S. Remote Sensing in Lineament Identification: Examples fromWestern India. J. Dev. Struct. Geol. Tecton. 2019, 15, 205–221.
11. Prost, G.L. Remote Sensing for Geoscientists; T & F Group, Ed.; CRC Press: Boca Raton, FL, USA; London, UK; New York, NY, USA, 2013; ISBN 9781466561755.
12. Gupta, R.P. Remote Sensing Geology; Springer: Berlin/Heidelberg, Germany, 2018; ISBN 978-3-662-55874-4.
13. Lausch, A.; Bannehr, L.; Beckmann, M.; Boehm, C.; Feilhauer, H.; Hacker, J.M.; Heurich, M.; Jung, A.; Klenke, R.; Neumann, C.; et al. Linking Earth Observation and taxonomic, structural and functional biodiversity: Local to ecosystem perspectives. Ecol. Indic. 2016, 70, 317–339.
14. Lausch, A.; Bastian, O.; Klotz, S.; Leitão, P.J.; Jung, A.; Rocchini, D.; Schaepman, M.E.; Skidmore, A.K.; Tischendorf, L.; Knapp, S. Understanding and assessing vegetation health by in situ species and remote-sensing approaches. Methods Ecol. Evol. 2018, 9, 1799–1809.
15. Kulkarni, H. Delineation of shallow Deccan basaltic aquifers from Maharashtra using aerial photointerpretation. J. Indian Soc. Remote Sens. 1992, 20, 129–138.
16. Kulkarni, H. Delineation of shallow Deccan basaltic aquifers from Maharashtra using aerial photointerpretation. J. Indian Soc. Remote Sens. 1992, 20, 129–138.
17. Fisher, G.B.; Amos, C.B.; Bookhagen, B.; Burbank, D.W.; Godard, V. Channel widths, landslides, faults, and beyond: The new world order of high-spatial resolution Google Earth imagery in the study of earth surface processes. In Google Earth and Virtual Visualizations in Geoscience Education and Research; Geological Society of America: Boulder, CO, USA, 2012.
18. Peyghambari, S.; Zhang, Y. Hyperspectral remote sensing in lithological mapping, mineral exploration, and environmental geology: An updated review. J. Appl. Remote Sens. 2021, 15, 031501.
19. Calvari, S.; Ganci, G.; Victória, S.; Hernandez, P.; Perez, N.; Barrancos, J.; Alfama, V.; Dionis, S.; Cabral, J.; Cardoso, N.; et al. Satellite and Ground Remote Sensing Techniques to Trace the

Hidden Growth of a Lava Flow Field: The 2014–2015 Effusive Eruption at Fogo Volcano (Cape Verde). Remote Sens. 2018, 10, 1115.

20. Sofia, G. Combining geomorphometry, feature extraction techniques and Earth-surface processes research: The way forward. Geomorphology 2020, 355, 107055.
21. Elosegi, A.; Díez, J.; Mutz, M. Effects of hydromorphological integrity on biodiversity and functioning of river ecosystems. Hydrobiologia 2010, 657, 199–215.
22. Corenblit, D.; Baas, A.C.W.; Bornette, G.; Darrozes, J.; Delmotte, S.; Francis, R.A.; Gurnell, A.M.; Julien, F.; Naiman, R.J.; Steiger, J. Feedbacks between geomorphology and biota controlling Earth surface processes and landforms: A review of foundation concepts and current understandings. Earth-Sci. Rev. 2011, 106, 307–331.
23. Stein, A.; Gerstner, K.; Kreft, H. Environmental heterogeneity as a universal driver of species richness across taxa, biomes and spatial scales. Ecol. Lett. 2014, 17, 866–880.
24. Sukopp, H. Der Einfluss des Menschen auf die Vegetation. Veg. Acta Geobot. 1969, 17, 360–371.
25. Lausch, A.; Blaschke, T.; Haase, D.; Herzog, F.; Syrbe, R.-U.; Tischendorf, L.; Walz, U. Understanding and quantifying landscape structure—A review on relevant process characteristics, data models and landscape metrics. Ecol. Modell. 2015, 295, 31–41.
26. Tarolli, P.; Cao,W.; Sofia, G.; Evans, D.; Ellis, E.C. From features to fingerprints: A general diagnostic framework for anthropogenic geomorphology. Prog. Phys. Geogr. Earth Environ. 2019, 43, 95–128.
27. Kulp, S.A.; Strauss, B.H. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Commun. 2019, 10, 4844.
28. Zheng, Z.; Du, S.; Du, S.; Zhang, X. A multiscale approach to delineate dune-field landscape patches. Remote Sens. Environ. 2020, 237, 111591.
29. Brown, A.G.; Tooth, S.; Bullard, J.E.; Thomas, D.S.G.; Chiverrell, R.C.; Plater, A.J.; Murton, J.; Thorndycraft, V.R.; Tarolli, P.; Rose, J.; et al. The geomorphology of the Anthropocene: Emergence, status and implications. Earth Surf. Process. Landf. 2017, 42, 71–90.
30. Le Provost, G.; Thiele, J.; Westphal, C.; Penone, C.; Allan, E.; Neyret, M.; van der Plas, F.; Ayasse, M.; Bardgett, R.D.; Birkhofer, K.; et al. Contrasting responses of above- and belowground diversity to multiple components of land-use intensity. Nat. Commun. 2021, 12, 3918.
31. Mock, J. Auswirkungen des Hochwasserschutzes. In Eine Einführung in die Umweltwissenschaften; Böhm, H.R., Deneke, M., Eds.; Wissenschaftliche Buchgesellschaft: Darmstadt, Germany, 1992; pp. 176–196.
32. Mock, J. Auswirkungen des Hochwasserschutzes. In Eine Einführung in die Umweltwissenschaften; Böhm, H.R., Deneke, M., Eds.; Wissenschaftliche Buchgesellschaft:

Darmstadt, Germany, 1992; pp. 176–196.