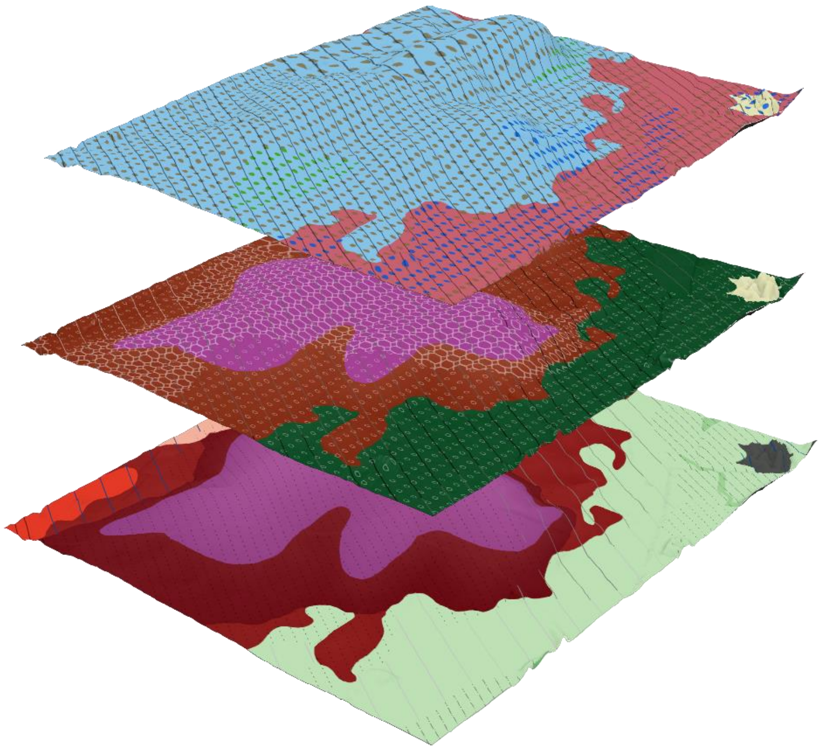
Mapping geodiversity in Texel



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Cover illustration: 3D layers of the results: three-tiered hierarchical geodiversity map. Made in ArcGIS Pro by the author.

Abstract

Currently, there is no standardized method for mapping the four principal components (geology, geomorphology, lithology, and hydrology) of geodiversity into a single digital map. Existing geodiversity assessments focus on individual components or grid-based index maps and ignore the scale-dependency of geofeatures. This research aims to standardize, test, and apply geodiversity mapping by utilizing a hierarchical taxonomy that allows for documenting geodiversity information at varying scales in a GIS environment. A coastal dune area and a Saalian push moraine area were selected as test areas on Texel Island in the Netherlands, characterized by contrasting geodiversity gradients. A semi-automated workflow is created that combines open-access geodiversity components in a single digital multi-scale hierarchical geodiversity map that has been checked in the field. The end-user can dynamically display the different taxonomic levels of all components and their geofeatures in a single map layer. The inclusion of a global geodiversity taxonomy in this mapping method results in the potential to scale up the method and conduct this research in a different environment, enhancing the interoperability of geodiversity research. The results demonstrate that additional classes, available in other environments can be added. The workflow and the resulting maps are a major step forward in the development of transparent, reproducible, and uniform hierarchical geodiversity maps.

Table of contents

1. Introduction

1.1 Relevance of geodiversity

The concept of geodiversity describes the variety of abiotic features on the Earth's surface and subsurface (Boothroyd et al., 2019; Gray, 2004). More precisely, geodiversity explains the natural range of the four major components geology (rocks, minerals), geomorphology (landforms, topography, physical processes), lithology (soil types and properties), and hydrology features (lakes, rivers) (Gray, 2013). Although the term geodiversity was introduced in the 1990s in Tasmania as a relatively new paradigm within the earth and environmental disciplines, geodiversity is now often used in environmental research (Gray, 2004; Hjort et al., 2024; Tukiainen et al., 2022a; Zwoliński et al., 2018). Awareness has risen that geodiversity is fundamental in understanding earth processes and provides a solid foundation for environmental management (Brilha, 2016; Gray, 2008; Knudson et al., 2018). For example, organisms depend directly or indirectly on biotic and abiotic components of nature, meaning that geodiversity is a cornerstone for biodiversity (Alahuhta et al., 2022; Tukiainen et al., 2022b; Lawler et al., 2015). Additionally, geodiversity actively contributes to several ecosystem services which are benefits humans receive from nature (Fox et al., 2022). The ecosystem services can be divided into four functions, regulating (regulation of thermal flows), provisioning (construction materials and rare-earth metals), supporting (habitat creation and maintenance), and cultural (aesthetic view and religious sites) (Fox et al., 2022; Gordon & Barron, 2013; Gray, 2013). Furthermore, due to anthropogenic activities, such as agricultural practices that may deplete the soil fertility, overexploitation of oil and rare earth materials, and urban sprawls, geodiversity changes rapidly (Gray, 2012; Van Ree & Van Beukering, 2016) and often irreversibly stressing the severity of geodiversity change (Gray, 2021; Tukiainen & Bailey, 2022). Therefore, research into the conservation and documentation of geodiversity features is vital for both humans and nature.

1.2 Previous research

Research has been done to assess geodiversity, especially quantitative research (Alahuhta et al., 2024; Chrobak et al., 2021; Ferrando et al., 2021; Gonçalves et al., 2022). However, due to the lack of a consensual definition of geodiversity, there is no universal classification or standards for the mapping and quantification of geodiversity components (Ibáñez & Brevik, 2022; Santos et al., 2017). In an effort to address this knowledge gap, a recent study by Hjort et al. (2024) proposes a new classification taxonomy to identify and document global geodiversity. The taxonomy includes features that are specific to the four main components of geodiversity and is tested in a high-latitude environment (Finland) at a local (5m radius) and landscape (500m x 500m) scale and extent. Since this research was recently published, the taxonomy has not been broadly tested yet. Therefore, the taxonomy needs to be tested in different environments, such as a low-altitude environment in the Netherlands.

Qualitative mapping methods are based on the visual representation of each geofeature within a component map (Gonçalves et al., 2022; Brilha et al., 2018). In the Netherlands, existing component maps were created between 1950 and 1990 using less advanced and precise tools (e.g. topographic contour line paper maps) than current methods (e.g. using LiDAR-based fine-scale digital maps) (De Jong et al., 2021; Minasny & McBratney, 2016; Verstappen, 2011). On paper maps, landscape features are shown in a single layer, which makes these maps difficult to read and not suitable for displaying multiple scales. This constraint emphasizes the need for a more holistic mapping approach. Several studies in geomorphology and soil science have used hierarchical mapping methods to overcome this limitation (Bucci et al., 2022; De Jong et al., 2021; Wielemaker et al., 2001). Few studies have attempted to use hierarchical mapping to combine geofeatures into one digital map. This suggests a research gap in the field of geodiversity mapping, where additional insight can be gained through utilizing hierarchical mapping approaches and integrating geodiversity features into a unified geodiversity map. Here, a novel method is applied to identify and map geodiversity at different scales using a three-level hierarchical geodiversity map. The aim is to apply the hierarchical geomorphological mapping method as proposed by De Jong et al. (2021) for three geodiversity levels proposed in the geodiversity taxonomy Hjort et al. (2024) on Texel Island.

1.3 Research aims and questions

To design and test the methodology, three research aims have been formulated: (1) develop a semi-automated hierarchical geodiversity mapping method following Hjort et al. (2024), (2) improve and visualize the geodiversity component maps in two study areas, and (3) assess the variety of geodiversity of the 'Hoge Berg' push moraine and the coastal dunes.

These research aims lead to the following research questions:

1. Which taxonomic levels and features of Hjort et al. (2024) are necessary to map the geodiversity of Texel Island?

2. Which digital cartographic visualization tools and techniques adequately display geofeatures in a hierarchical geodiversity map?

3. What geodiversity components and classes are present in the 'Hoge Berg' and the dune areas?

2. Theoretical framework

2.1 Study area

Texel is located in the northern part of the Netherlands (Figure 1). Texel is the largest Dutch Wadden island in the North Sea measuring approximately 170 km2 and was formed approximately 6000 years ago (Seijmonsbergen et al., 2021). The island is characterized by a highly diverse landscape in a relatively small area. Almost every geodiversity feature present in the Netherlands is also found on Texel (De Jong, 2015). Texel has a strong environmental gradient compared to its size which makes Texel a suitable research area within the scope of this thesis. Two case study areas of 6 km2 are selected, one in the nature reserve 'Hoge Berg' and one in the dunes (Figure 1). The two areas have completely different geomorphology and vary in geology, soil, and hydrology features.

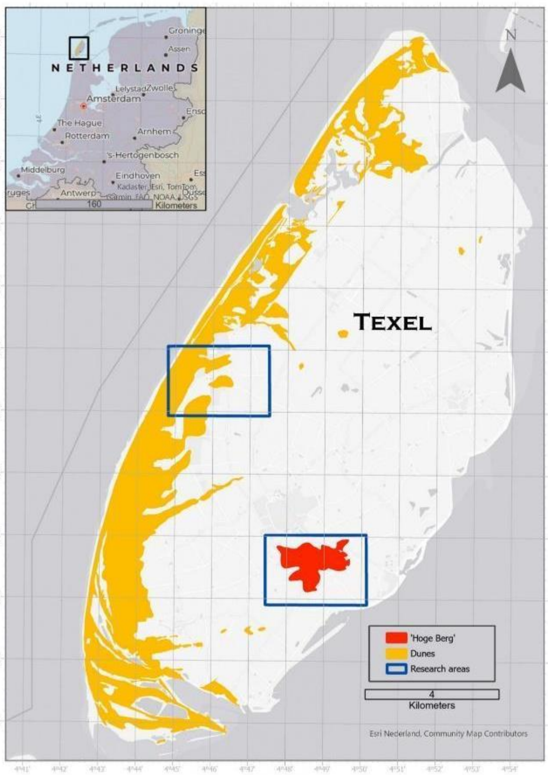

Figure 1. Overview of Texel and the case study areas

Hoge Berg

The 'Hoge Berg' is a small nature reserve developed as a boulder-clay underlain push moraine reaching approximately 15 m above sea level (De Jong, 2015). The push moraine was formed during the 'Saalian' in the second last glacial period approximately 150 thousand years ago (Seijmonsbergen et al., 2021). During the last ice age, the 'Hoge Berg' remained free of ice. Therefore, aeolian and mass movement processes highly affected the geomorphology producing cover sand deposits and reworking of the subglacial till. The most common materials are sand, clay, silt, and occasionally gravel. Due to its topography and mix of permeable and less-permeable materials, the groundwater level broadly follows the surface topography (Seijmonsbergen et al., 2021). Until 1925, a part of the area was used to extract sand and loam (Weertz et al., 2011). The former sand pit has since been transformed into an insect sanctuary where biodiversity can flourish. Another part of The 'Hoge Berg' is covered with an oak forest and the surroundings of the 'Hoge Berg' are gentle sloping meadows where sheep graze. Furthermore, in 2019 the nature reserve was named 'Icoonlandschap' of the Netherlands due to its visible geomorphological history, rich flora and fauna, and natural and cultural value of the landscape (Vereniging Nederlands Cultuurlandschap, 2019). An example of the natural and cultural value in this area is the utilization of 'tuunwallen' as parcel dividers. This method is specifically used in Texel and cannot be found in many other places. 'Tuunwallen' are man-made linear structures made of 'plaggen', which is excavated organic topsoil and grass. A variety of insects live in this man-made structure and in the summertime flowers bloom on the 'tuunwallen', enhancing biodiversity and revealing the natural value of this in essence cultural structure. (Vereniging Nederlands Cultuurlandschap, 2019).

Figure 2. Landscapes and landscape elements of the 'Hoge Berg' case study area. (A) View of the former sand pit which has been transformed into an insect sanctuary resulting in a biodiversity hotspot. (B) View of gently sloping meadows with grazing sheep (C) View of the oak forest- covered part of the 'Hoge Berg'. (D) Detailed view of the 'tuunwallen' as parcel dividers along an artificial pond for cattle to drink.

Dunes

The dunes of Texel have been a part of the 'National Park Dunes of Texel' since 2002 covering the entire western coastline of the island in an area of approximately 43 km2 (Seijmonsbergen et al., 2021; Welkom in Nationaal Park Duinen van Texel, z.d.). The dunes of the case study area are located close to the town 'de Koog' and are part of the old dunes of Texel (at least 500 years old). In the area, parabolic dunes, blowouts, dune slacks, dune valleys, and enclosed beach plain landforms have developed. The valleys are deflated to the groundwater level, resulting in dry and wet dune valleys (Duinen Tussen de Koog en Den Hoorn - Ecomare, 2019). Furthermore, the dunes in this area are largely part of the gray dunes while some parts are characterized as white dunes of Texel according to the habitat type map of Texel (database of EUNIS by EEA) (EUNIS -Site Factsheet For Duinen en Lage Land Texel, z.d.). Gray dunes are stabilized and colonized with grass communities and vegetation whereas white dunes are mobile dunes and not colonized by vegetation (database of EUNIS by EEA (EUNIS -Site Factsheet For Duinen en Lage Land Texel, z.d.). The dunes in the case study areas were once dune bow complexes but are now connected. The dune arches face west and the arms point east due to the prevailing wind from the northeast in the North Sea (Meijer et al., 2017). The dunes in Texel, specifically white dunes, are dynamic landforms that are still developing actively and have a function as a natural coastal defense mechanism (Farrell et al., 2023). In addition, the dunes also have a recreational function as the dunes are part of a large national park with 17 established walking routes varying from lengths between 0,5 km to 20 km (Wandelen, z.d.).

Figure 3. Landscapes and landscape elements of the dune case study area. (A) View of an active blowout. (B) View of a wet dune valley with parabolic dunes in the background. (C) Overview to the northeast of the central part of the study area. Dunes built on marram grass are present in the foreground and the active blowout of photo A highlighted by the red arrow is in the background.

2.2 Available geodiversity component maps

The current geomorphology and soil maps are from 'Basis Registratie Ondergrond' (BRO) and are openly available at 'Publieke Dienstverlening op de Kaart' (PDOK). The maps are based on field inventories between 1970-2004 and present landforms, soil types, and topography in the Netherlands at a scale of 1:50.000. The geomorphological legend is hierarchically structured into three levels of landforms, based on morphology in the upper level, genesis in the second level and relief and specific properties in the most detailed third level (Maas, Van Delft & Heidema, 2017). The legend of the soil map is based on the Dutch soil classification proposed by De Bakker et al. (1989) resulting in over 1700 unique soil classifications (*Bodemkaart legenda*, z.d.). The existing geological map is part of 'Geologische Dienst Nederland' (GDN) and is publicly accessible at 'Data en Informatie van de Nederlandse Ondergrond' (DINOloket). The geological map was prepared between 1950 and 1997 at a 1:50.000 scale. The hydrology component map is part of the 'Basis Registratie Topografie' (BRT) TOP10NL and is openly attainable at PDOK. The BRT is a topographic map including various elements with nationwide coverage and is available in different scales. The topographic element 'waterdeel' of the BRT TOP10NL is here utilized as the hydrological component.

2.3 Hierarchical mapping method

Methodological research into hierarchical mapping, especially for soil and geomorphological maps has been done by De Jong et al. (2021) and Wielemaker et al. (2001). The hierarchical method proposed by De Jong et al. (2021) is used as an adequate and recently developed GIS-based hierarchical mapping technique. The method uses a GIS database of classical geomorphological and geological maps, aerial images, and LiDAR-derived data. In essence, hierarchical mapping is used to transform classical geomorphological maps into computer-generated maps. The hierarchical map is divided into three tiers with a corresponding suggested scale range. Tier 1 visualizes the environments, followed by Tier 2 showing the process groups, and Tier 3 showing the morphogenic domains. Tier 1 offers a first impression of the predominant processes and landforms in the environment, while Tier 2 shows the distribution of the process groups and offers information on a regional scale. Tier 3 is the most detailed level which is suitable for applications on a local scale. The different tiers allow users to easily select the optimal scale for their application as the information density changes simply by zooming in or out. Additionally, De Jong et al. (2021) published a GIS workflow for automating the process in ArcGIS Pro. This model automatically adds Tier 1 and 2 based on the GIS code provided with the Tier 3 attribute table.

2.4 Geodiversity taxonomy

A first step towards developing a global geodiversity taxonomy has been proposed by Hjort et al. (2024). Their hierarchical taxonomy aims to be a simple, adaptable, and transferable classifying system focusing on geofeatures that are specific to the geodiversity components: Geomorphology, Geology, Soil, and Hydrology. The hierarchical structure of the taxonomy is composed of six levels. The components of geodiversity form the first taxonomic level of the hierarchical system. In the second level, the components are subdivided into nine classes of geofeatures based on the genesis of the geofeature. The geofeatures classes are then subdivided into geofeature groups in the third taxonomic level of the taxonomy and then further divided into subgroups of geofeatures in the fourth level. Both geofeature groups and their subgroups are based on their physical-chemical properties. At the fifth and sixth taxonomic levels are geofeatures and its subtype, which can consist of tens of thousands of subtypes. An preliminary example of the geodiversity taxonomy adjusted for Texel is shown in Figure 4. The other geodiversity components' taxonomies can be found in Appendix A.2.

L1_Component	L2_Geofeature class	L3_Geofeature group	L4_Geofeature subgroup	L5_Geofeature
B: Geology	rocks	igneous	intrusive	gabro / diorite / granite /
			extrusive	basalt / andesite / rhyolite /
		sedimentary	clastic	conglomerate / breccia /
			chemical	limestone / dolostone /
			biological	coal / chert /
		metamorphic	foliated	slate / schist / gneiss /
			non-foliated	quartzite / marble /
	sediments and materials (1000)	mechanical (1100)	diamicton or unsorted (1110)	till / gravitational diamicton /
			very coarse (1120)	blocks (boulder) / stones (cobble)
			coarse (1130)	gravel (pebble) / sand
			fine (1140)	clay / silt /
		chemical	diamicton or unsorted	diamicton or unsorted /
			very coarse	blocks (boulder) / stones (cobble)
			coarse	gravel (pebble) / sand
			fine	clay / silt /
		organic (1200)	peat (1210)	sapric-eutrophic /
			other organic material (1220)	autochthonous-plant origin /

Figure 4: The geological taxonomy as proposed by Hjort et al. (2024) adjusted to features present in Texel. The component geology is divided into 5 different levels.

3. Methodology

In this chapter, the methods utilized to develop a hierarchical geodiversity map are outlined. The methodological steps are visualized in a workflow (Figure 5) which was created to make the research transparent, efficient, and reproducible. Four different routines are visualized in the workflow: 1. data collection, 2. (pre)processing, 3. visualization, and 4. validation and analyses. Each routine and its corresponding steps are described in the subsequent sections of this chapter.

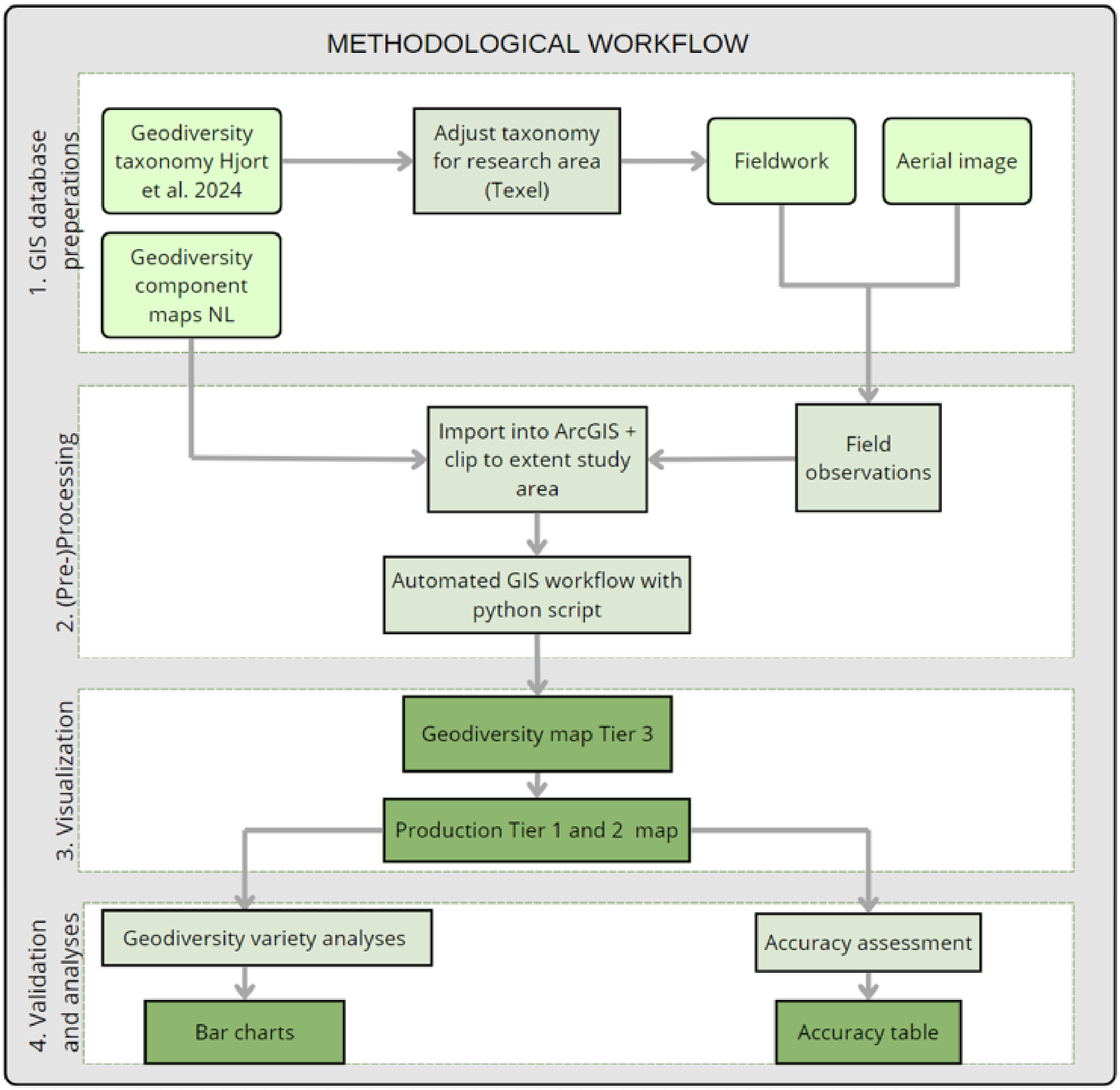

Figure 5. Research workflow. The light green boxes are input data layers, the green boxes represent method and tool steps and the dark green boxes are visualizations or results.

3.1 Data collection

The first routine in the process of developing a hierarchical geodiversity map is data acquisition. The outline of Texel is extracted from the CBS (2023) which registers municipality boundaries of the Netherlands. To represent the geodiversity components, four data layers are downloaded from the ‘Basisregistratie ondergrond’ (BRO) and ‘Geologische Dienst Nederland’ (GDN) via the ArcGIS living atlas in ArcGIS pro (Table 1). An overview of the metadata is presented in Table 1.

Table 1. Metadata and maps used for developing hierarchical geodiversity map

Name	Metric	Type	Scale/resolution	Reference system	Source
Texel Boundary	Shape of Texel	Vector – Polygon	1:750.000 – 1:160.000	RD – New EPSG:28992	CBS (2023) https://www.arcgis.com/home/item.html?id=90e528e0dd194a2380dbddc7d0aca051
Geomorphology Texel	Geomorphological units	Vector – Polygon	1:50.000	RD – New EPSG:28992	BRO (2024) https://www.arcgis.com/home/item.html?id=5d59b72aa2c34f06a88bb045a9770c4b
Geology Texel	Geological units	Vector – Polygon	1:50.000	RD – New EPSG:28992	Geologische dienst Nederland (2023) https://www.dinoloket.nl/geologische-kaart
Soil Texel	Soil units	Vector – Polygon	1:50.000	RD – New EPSG:28992	BRO (2024) https://www.arcgis.com/home/item.html?id=ee1d6acb82fe4f1d9b2442ff050015a4
Hydrology Texel	Water units	Vector – Polygons and lines	1:50.000	RD – New EPSG:28992	BRTTop10 (2024) https://basisregistraties.arcgisonline.nl/arcgis/rest/services/BRT/BRT_TOP10NL/MapServer
Aerial image Texel 2022	Additional geofeature details	Raster	8cm x 8cm	RD – New EPSG:28992	Beeldmateriaal Nederland (2023) https://www.arcgis.com/home/item.html?id=d29464d3a2b442a6aa226706207db94e

Fieldwork

In-field validation of the component maps is necessary since most data was collected between 1960 and 1990. To ensure uniformity, and comparability and minimize errors during the data collection phase, a detailed checklist is used at each observation point. This process was done digitally, a virtual fieldwork map was created utilizing the ArcGIS Fieldmaps app which allows for simple data transfer to ArcGIS Pro. The backup field form that could be filled out manually is presented in Appendix A.1. Furthermore, approximately 30 randomly selected points were selected for both the 'Hoge Berg' and the dune area. However, care was taken to ensure that each geodiversity component class was represented by at least one sample point, thus some points were slightly adjusted. These points were visited, and the components - landform, material, hydrological properties, and primary soil type - were evaluated and assigned a GIS code according to the highest level applicable to the geodiversity taxonomy (see Figure 6). In the dunes research area, a total of 36 sampling points were collected, consisting of five observational points and 31 points with soil indications. In the ‘Hoge Berg’ study area, 37 sampling points were collected, consisting of 14 observational points and 23 points with soil indications. The data analyses of these sample points will be visualized and discussed in chapters 4.2 and 5.2. Component maps of the case study areas, including the BRO, BRT maps, hillshade, and contour lines, combined with field observations, were used to assess the landform and hydrological properties The texture was evaluated by using a sand ruler or by doing a clay/loam test utilizing the USDA soil texturing field flow chart (IUSS Working Group WRB, 2022). With a small spade, a cube of approximately 20 cm by 20cm was taken to assess the texture and estimate the organic content class (organic, mixed, or mineral). Additionally, pictures were taken for each point in order to review data points easier in the processing phase. Finally, all the collected data is imported into ArcGIS.

L1_Component	L2_Geofeature class	L3_Geofeature group	L4_Geofeature subgroup	L5_Geofeature
A: Geomorphology	Exogenic features (1000)	Erosion (1100)	Glacial (1110)	Valley (1111)
			Marine (1120)	Curves in sand banks (1121)
				Plain (1122)
				Marine erosion channel (1123)
				Tidal plain (1124)
				Flood plain (1125)
				Breach plain (1126)
			Aeolian (1130)	Dune valley (1131)
				Dune slope (1132)
				Parabolic dune (1133)
				Blowout (1134)
				Old dune (1135)
			Biotic (1140)	Cliff (1141)
		Deposition (1200)	Glacial (1210)	Push moraine (1211)
			Marine (1220)	Sand sheet (1221)
				Tidal deposition (1122)
				Enclosed beach plain (1223)
				Beach ridge (1224)
				Curves in tidal accretions (1225)
				Curves in tidal deposits (1226)
				Beach plain (1227)
				Tidal levee (1228)
			Aeolian (1230)	Sand sheet (1231)
				Dunes with plains (1232)
				Sand shoal (1233)
				Lösscover (1234)
				Belt sand curvatures (1235)
				Belt sand ridge (1236)
			Organic (1240)	Peat plain (1241)
	Anthropogenic features (2000)	Erosion (2100)	Erosion (2110)	Sand pit (2111)
				Plain (2112)
				Valley (2113)
				Waste ppit (2114)
		Anthropogenic (2200)	Anthropogenic (2210)	Dike (2211)
B: Geology	Sediments and materials (1000)	Mechanical (1100)	Diamicton or unsorted (1110)	till (1111)
			Coarse (1120)	Sand (1121)
				Sand/clay (1122)
				Gravel (1123)
				Gravel/clay (1124)
			Fine (1130)	Sand (1131)
				Clay/sand (1132)
				Clay (1133)
				Loamy sand (1134)
			Mixed (1140)	Sand (1141)
				Clay/sand (1142)
				Peat/sand (1143)
		Organic (1200)	Peat (1210)	Peat (1211)

C: Soil	Mineral (1000)	Young (1100) Moderate (1200) Old (1300)		
	Mixed (2000)	Young (2100) Moderate (2200) Old (2300)		
	Organic (3000)	Young (3100) Moderate (3200) Old (3300)		
	Mixed/Mineral (4000)	Young (4100) Moderate (4200) Old (4300)		
D: Hydrology	Surface water (1000)	Standing water (1100)	Ditch (1110) Temporary water (1120) Pond (1130)	

Figure 6. *Developed geodiversity taxonomy for the extent of Texel*

Hierarchical mapping with a geodiversity taxonomy

The hierarchical mapping method proposed by De Jong et al. (2021) for geomorphology in mountainous areas is utilized to map geodiversity hierarchically. Here, a structure to systematically classify both geomorphological features and geological, soil, and hydrological features is needed. The geodiversity taxonomy as proposed by Hjort et al. (2024) is used with some adjustments to make the taxonomy applicable to Texel. As the input layers came from Dutch sources, the classifications are in Dutch. Therefore, the classifications of all the data layers are translated to match the geodiversity taxonomy equivalent.

The Dutch geomorphological map and classifications corresponded neatly with the geodiversity taxonomy. Only a few adjustments were made, mainly in translation and the presence of certain geofeatures. To be more precise, the endogenic and extraterrestrial features of the second level are omitted as well as the weathering, mass movement, and cryogenic features of the third level as these features are absent in Texel. Specific geofeatures (i.e. push moraine, marine erosion channel, and sand pit) present in Texel were added in the fifth level of the taxonomy (Figure 6).

The Dutch geological classification did not correspond neatly with the geodiversity taxonomy since it overlapped with the Dutch geomorphology classification and did not correspond to the material of the subsurface. Which is the base of the geological geodiversity taxonomy classification. Therefore, the geological information needed to match the Hjort et al. (2024) taxonomy was extracted from the digital Dutch soil maps which include material type and texture data.

The Dutch soil classification did not correspond with the soil types proposed in the geodiversity taxonomy of Hjort et al.(2024). Following communication with Dr. A.M. Kooijman (IBED landscape ecologist, personal communication, May 17, 2024), she explained that due to the relatively young age of the soils in Texel, the Dutch soil classification cannot be converted to the World Reference Base (WRB) soil type classification, as proposed in the Hjort et al (2024) taxonomy. Therefore, a different soil classification was produced. This new soil classification is based on the predominant soil layer (mineral, mixed, or organic layer) for which expert knowledge and soil sample data collected during the fieldwork were utilized. For the classification of 'mineral' and 'mixed', a threshold of 50% was used to classify the soil sample as mineral or mixed soils. However, for the organic soil classification, a threshold of 30% was chosen based on research by Huang et al. (2009) which states that soil with more than 30% organic content can be classified as highly organic soils. Furthermore, the predominant soil layers are further classified into soil age categories of young, moderate, and old age based on expert knowledge.

The hydrological data of the BRT contains more than 200.000 features within the extent of Texel. Given the time constraint, the hydrological component could not be analyzed fully. Therefore, the hydrological component was excluded from data analysis and only visualized in the hierarchical geodiversity map.

For mapping purposes it is essential that geofeature names are unique. In the taxonomy for Texel some duplicate names occur, for example, the geofeature 'valley' occurs twice in the geomorphological component (Figure 6). However, the process group described in the fourth level of the taxonomy differs as a valley can be formed by either glacial exogenic activities or anthropogenic activities. In order to solve this, unique GIS codes, as proposed by De Jong et al. (2021), were added to the taxonomy. The unique GIS codes ensure differentiation between classes and correct hierarchical mapping. The adapted geodiversity taxonomy and corresponding GIS codes for Texel can be found in Appendix B.

3.2 (Pre-)Processing

All data (Table 1) is imported into ArcGIS and the geodiversity component maps are clipped to the extent of Texel. Field observation points were added to the project. A conversion table (see Appendix A.3) based on the data of the Dutch component maps was made with all the translation of the classifications per geodiversity component. Second, the highest level taxonomy classification corresponding name and GIS code is manually added in all conversion tables. Subsequently, the lower levels of the taxonomy and its codes are based on the GIS code of the highest taxonomic level and appended automatically to the conversion table using a Python script. Afterward, the conversion table is merged with the corresponding geodiversity component feature layer in ArcGIS Pro utilizing the 'join' tool. The result is a complete and hierarchically structured features layer per geodiversity component for Texel.

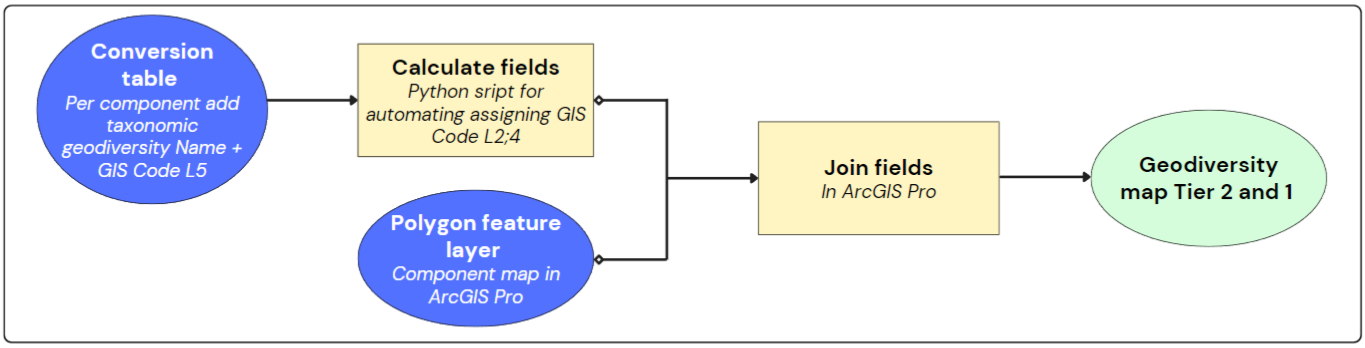

Figure 7. *Workflow visualizing the GIS code translation automation. The blue circles represent input data. The yellow boxes are the method and tools used. The green circle visualizes the results.*

3.3 Visualization

The digital multi-level geodiversity map was made utilizing the workflow visualized in Figure 7. Subsequently, the different taxonomy levels are visualized by utilizing symbology adjustments for each geofeature per component and taxonomic level. Furthermore, the recommended scale range per level of the hierarchical geodiversity map is based on the methodology of De Jong et al. (2021), which also delineates three tiers for their geomorphological map. For the highest tier (1), a scale greater than 1:30,001 is recommended; for the intermediate tier, a scale between 1:30,000 and 1:10,001 is advised; and for the lowest tier (3), a scale between 1.2,500 and 1:10,000 is suggested. The scale choice depends on the end-user's application and can be adjusted accordingly. To summarize, the hierarchical geodiversity map is produced by integrating existing component maps, refining the symbology to improve readability, and validating selected sample points through field observations and aerial images.

3.4 Validation

The accuracy of the map is assessed per component by comparing the field observation classification points to the geomorphological and geological component map. To calculate the accuracy, the number of total matches was divided by the total number of observations for each component. The result was then multiplied by 100. The calculation is shown in Equation 1. The detailed accuracy assessment, in which the accuracy per class is calculated, is visualized in bar charts and presented in chapter 4.1. Given that the number of sample points is limited, the accuracy is calculated in percentages to highlight the proportional relationships rather than an accuracy count as the sample size was small.

$$Accuracy\ score = \frac{Observed\ value}{Total\ value} \times 100\% \tag{1}$$

The classification boundaries of the misclassified polygons were modified based on the field observations and if necessary aerial images were utilized for more precise readjustments to improve the hierarchical geodiversity map. The split tool in ArcGIS Pro was utilized to correct the polygons.

3.5 Geodiversity variety assessment

Bar charts and a correlation matrix were made to assess the variety of geodiversity of the 'Hoge Berg' push moraine and the coastal dunes. The bar charts and correlation matrix show the frequency and distribution of the geodiversity features per research area and are made using Python, specifically the matplotlib and pandas libraries.

4. Results

This chapter will present the results. The mapping results will be discussed first and afterward, the data analyses of the geomorphological, geological, and soil features will be discussed.

4.1 Mapping results

The multi-scale hierarchical geodiversity map is shown in Figures 8.a, 8.b, 8.c, 9.a and 9.b. Figure 8.a shows an overview of Texel on the first-tier: environments. Figure 8.b illustrates the same extent for the second-tier: processes. Figure 8.c shows an overview of Texel on the third-tier: domains. Figures 9.a and 9.b show the geodiversity maps of the research areas 'Hoge Berg' and Dunes in all three tiers. The legend of this map is conceptually multi-level and hierarchical as it generally aligns with levels 3-5 of the geodiversity taxonomy of Hjort et al. (2024).

The geomorphological features are visualized in different colors. All geomorphological classifications and the corresponding colors are outlined in the legend shown in Figure 10. The geological component is visualized utilizing various colors and widths of striped patterns to differentiate geological material and texture. The first-tier map has two geological classifications which are visualized with black colored stripes for mechanical geology and green stripes for organic geology. In the second-tier map, different shades of gray are used to differentiate between coarse, fine, and mixed geology, and green stripes are used to visualize peat features. A blue color was used to visualize mixed geology features in the third-tier map and the fine and coarse geological features remain visualized in shades of gray. For the third-tier map, less wide striped patterns are used for the classifications of fine texture geology, whereas wider stripes are used for mixed texture features, and the widest striped pattern is utilized to visualize coarse texture materials. Furthermore, the material clay and loamy sand are visualized with dashed lines. To visualize peat and mixed peat/sand classification, the striped pattern was rotated 45 degrees to the left. The soil component features are visualized in different colored dots in the first-tier map and different sizes of colorless hexagon shapes in the second-tier map. In the first-tier map, the mineral soils are visualized with brown dots whereas mixed soils are visualized with blue dots and organic soils with green dots. For the second-tier map, the soil age classification is visualized as different sizes of hexagons. The old soils are depicted as the largest hexagons and the young soils as the smallest hexagons.

Improvements to the existing component maps were made by adjusting the classifications and GIS codes based on the new classifications observed during the fieldwork. Notably, improvement was needed in the Tier 3 maps for the dune area given that other classifications were observed in the dunes during the fieldwork. Therefore, more detailed classes such as dune slopes, blowouts, dune valleys, parabolic dunes, and old dunes were added to the map.

The multi-level hierarchical geodiversity map is available in the project package of the ArcGIS Pro workspace, which can be downloaded using the link provided in Appendix E.

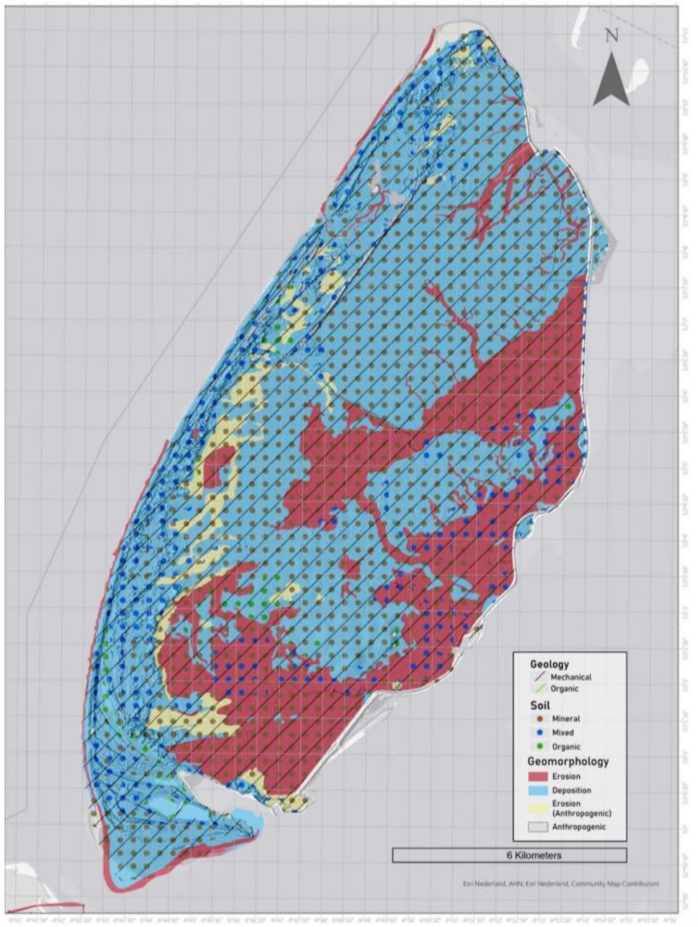

Figure 8.a. Overview of the first-tier map Texel

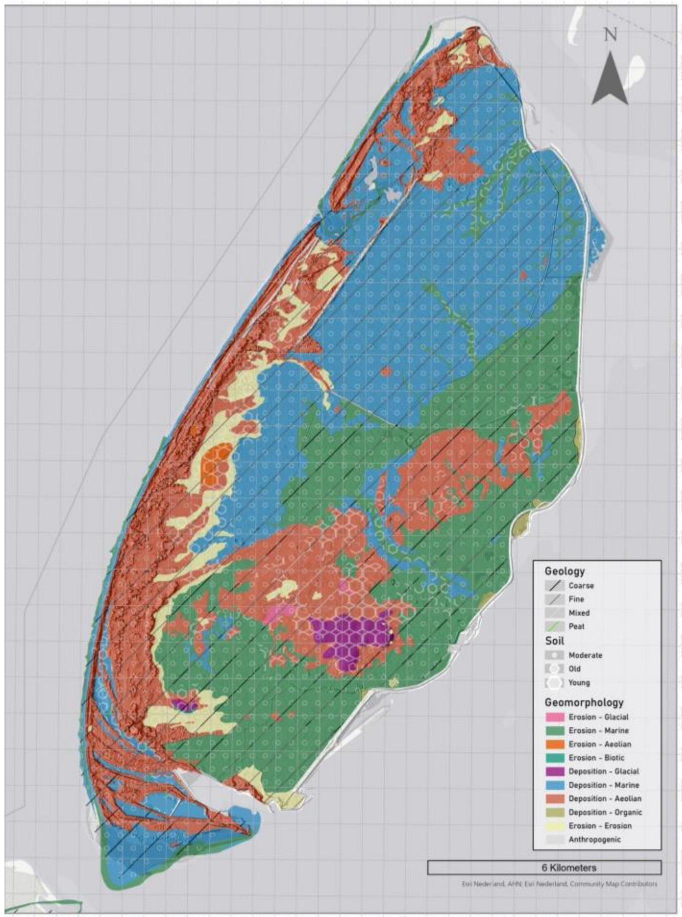

Figure 8.b. Overview of the second-tier map Texel

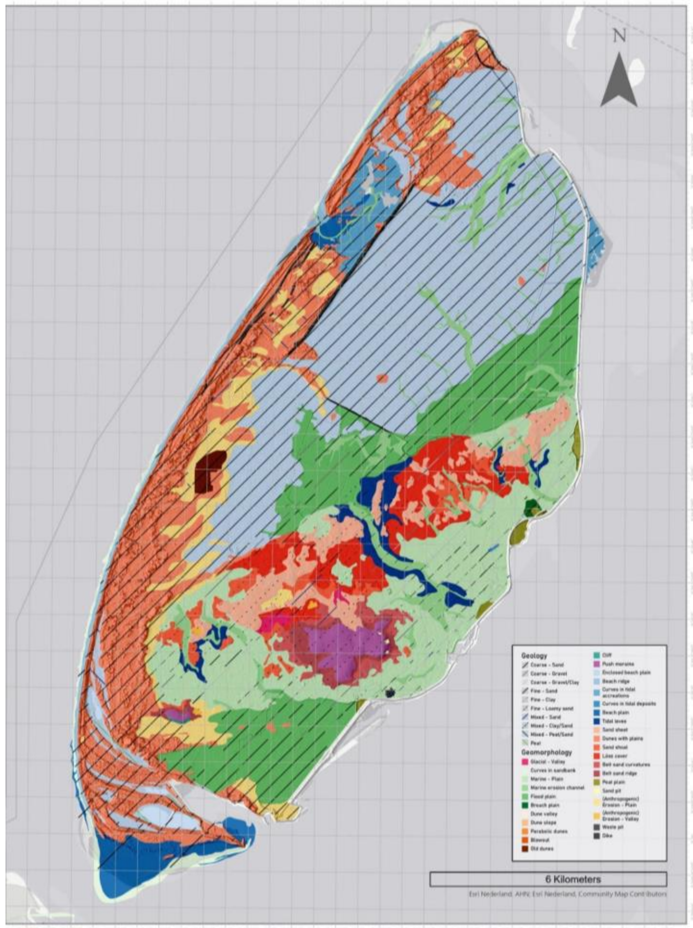

Figure 8.c. Overview of the third-tier level map Texel

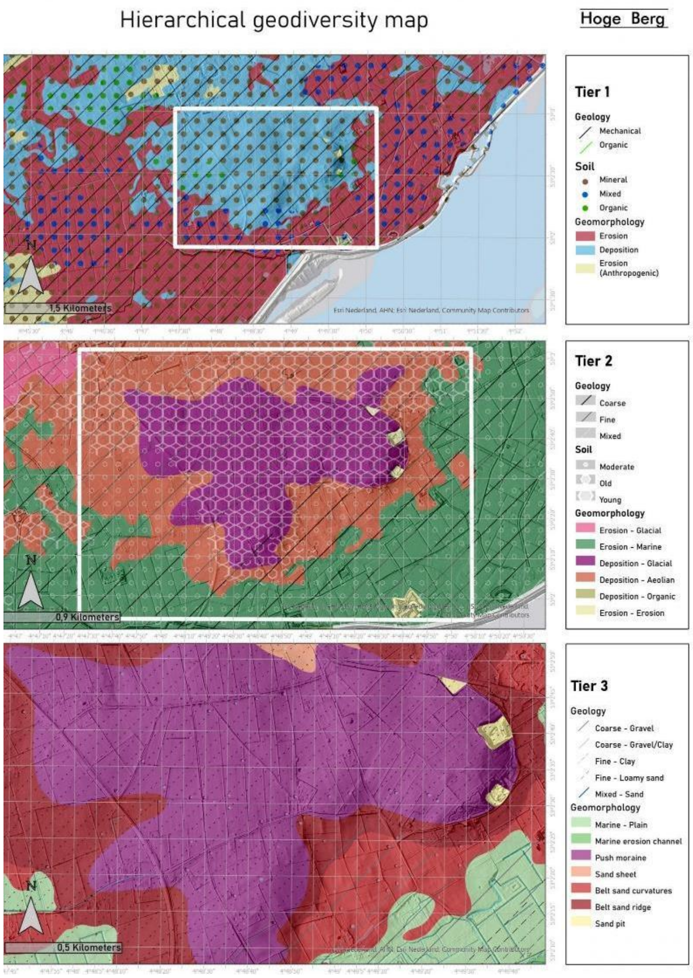

Figure 9.a. 'Hoge Berg' hierarchical geodiversity map

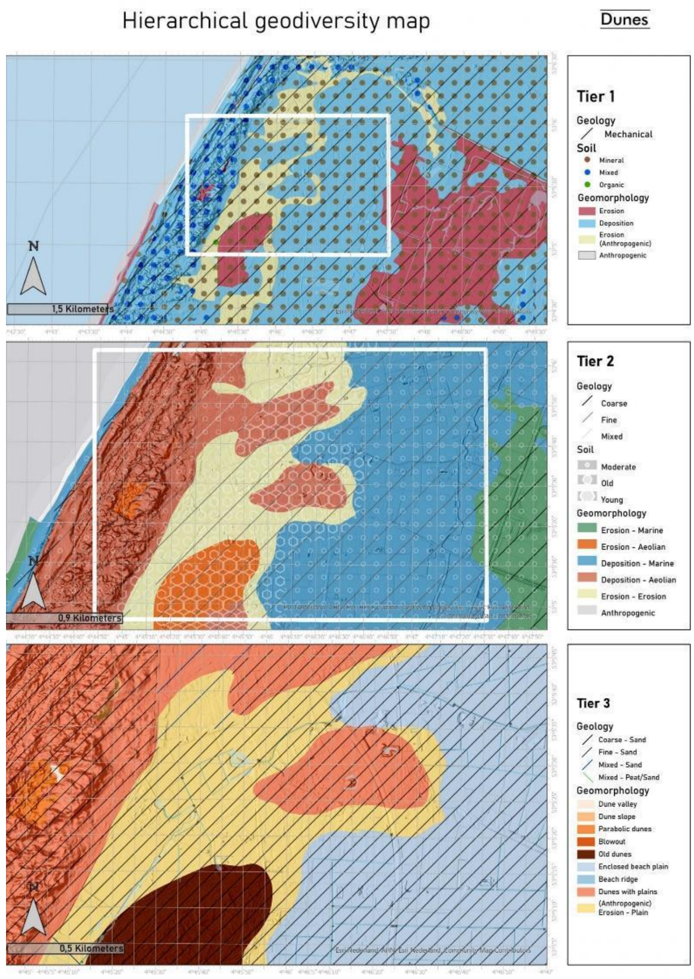

Figure 9.b. Dunes hierarchical geodiversity map

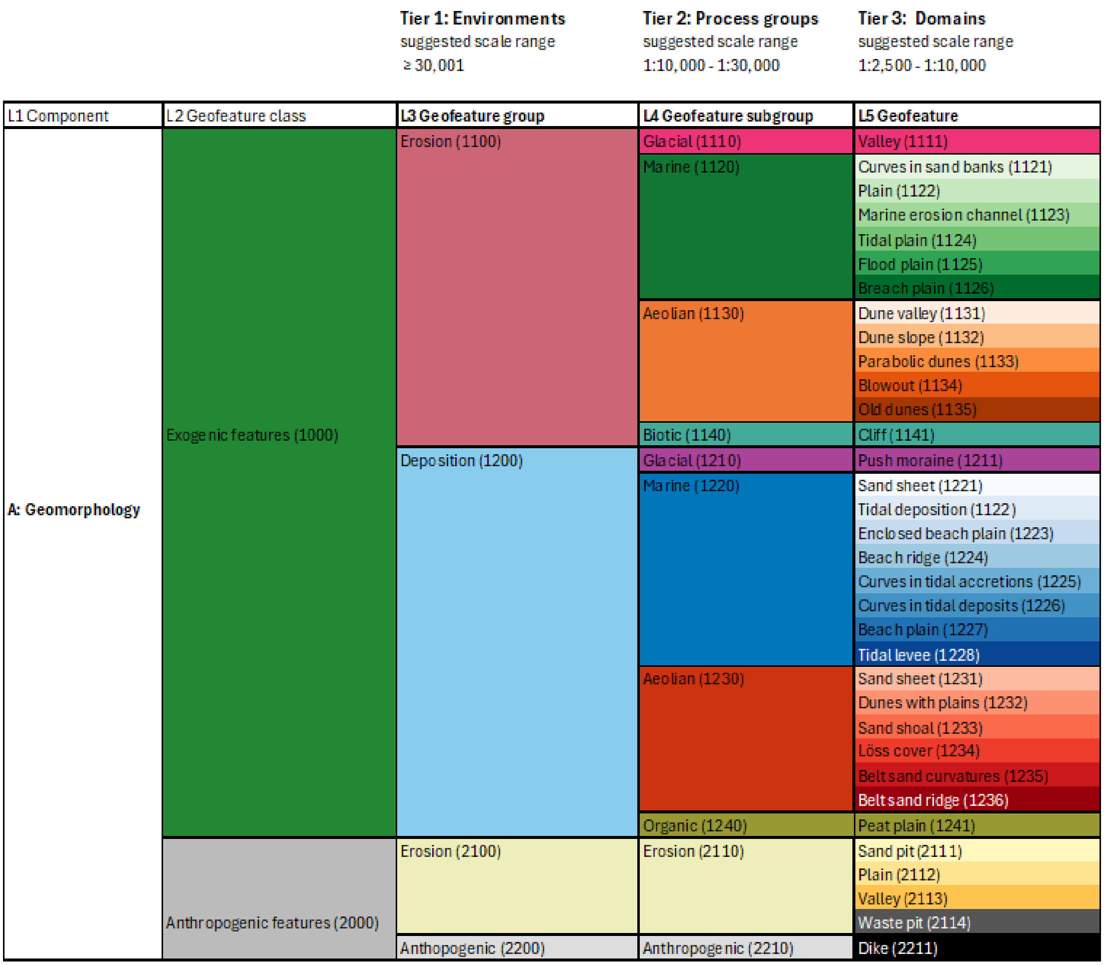

Figure 10: Legend showing the colors chosen for each geomorphological feature at the different taxonomic levels.

Accuracy assessment

In the 'Hoge Berg' area, 87% of the geomorphological field observations matched the original geomorphological map (Table 2). In the dune area, 61% of the observations are in agreement. For the geological component of the developed map, 35% of the observations in the 'Hoge Berg' area matched the original geological map, while in the dune area, the match was 84%. The accuracy assessment results indicate significant variability in agreement between the research areas. Specifically, the 'Hoge Berg' area exhibits a very low accuracy score of 35% for the geological components, whereas the geomorphological component has a relatively high accuracy score of 87%.

Table 2: Accuracy assessment of the multi-level hierarchical geodiversity map for two geodiversity components categorized for each case study area in percentages using the formula as described in chapter 3.4. Additionally, the total observations from which the accuracy assessment is calculated are shown per case study area and component.

Geodiversity component	Accuracy Hoge Berg (%)	Accuracy Dunes (%)	Total observations HB	Total observations Dunes
Geomorphology	87	61	27	31
Geology	35	84	23	31

In the 'Hoge Berg', the categories - push moraine, sand pit, and tidal deposits - were consistently in agreement. In contrast, the cover sand ridge and marine erosion channel classes were each misclassified once. In the dunes, the geomorphological feature 'dunes with plains' were misclassified in all 12 observations, whereas the classifications for enclosed beach plain and plain were always accurate. It is notable that in the dune area, the category 'dunes with plains' is subdivided into more detailed classes in the new landform classifications bar chart (Figure 11.a). This subdivision of a specific classification is not as apparent in the 'Hoge Berg' case study area, thus resulting in a higher accuracy score.

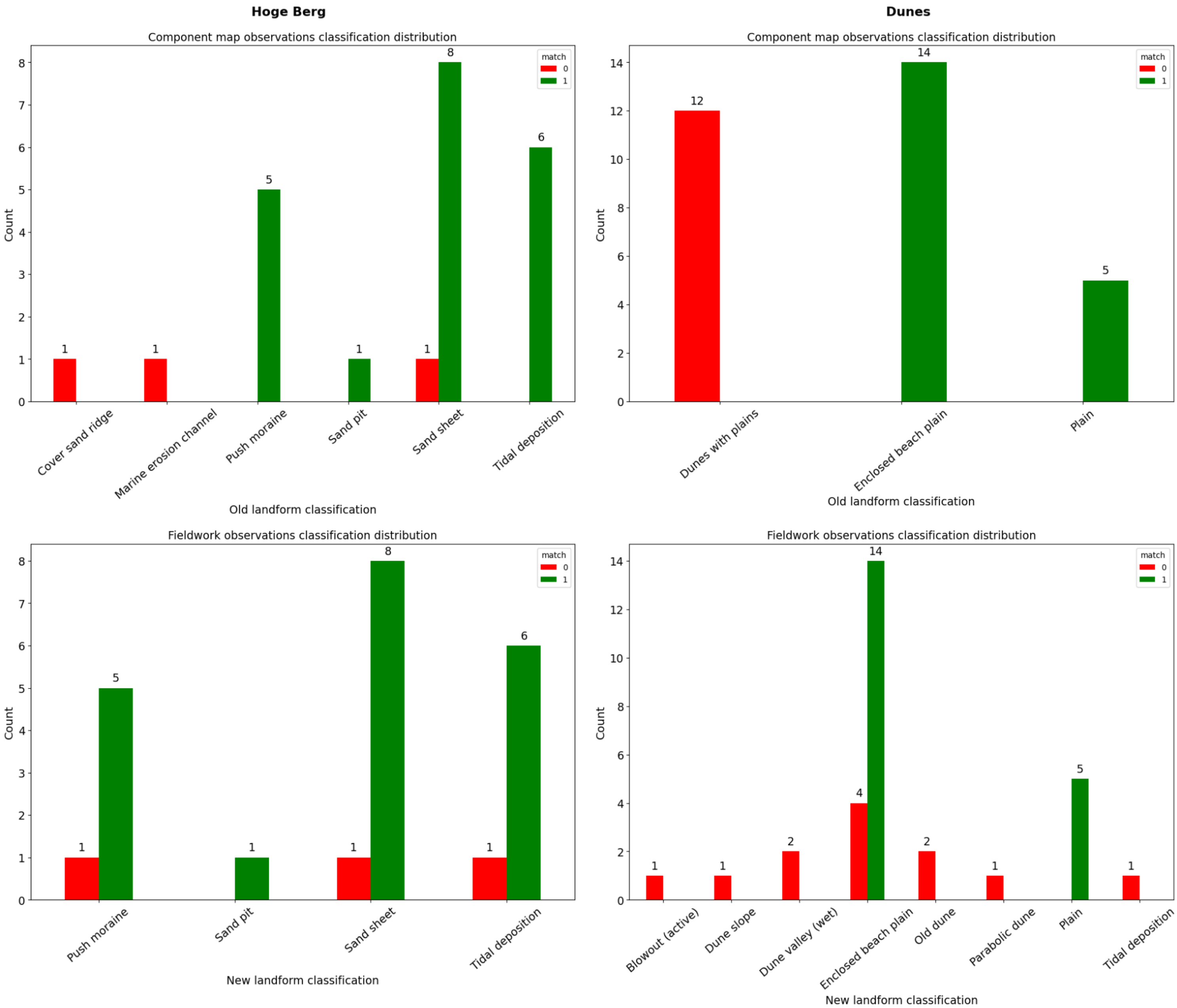

Figure 11.a: Detailed agreement counts per geomorphological classifications for both case study areas

The geological component has a higher accuracy score in the dune area (84%) compared to the 'Hoge Berg' area (35%). In the 'Hoge Berg' case study area, clay was consistently misclassified, while sand was misclassified 50% of the time. In the dune area, sand was correctly classified in 26 out of 30 observations, whereas peat/sand was misclassified once. The analysis in the dune area also indicates a more detailed classification following field observations. Although sand remains the most frequently classified class in the dunes, with 27 observations out of 31. It should be noted that the geological classes observed during the fieldwork in the dunes are less evenly distributed compared to the distribution in the ´Hoge Berg´ area (Figure 11.b).

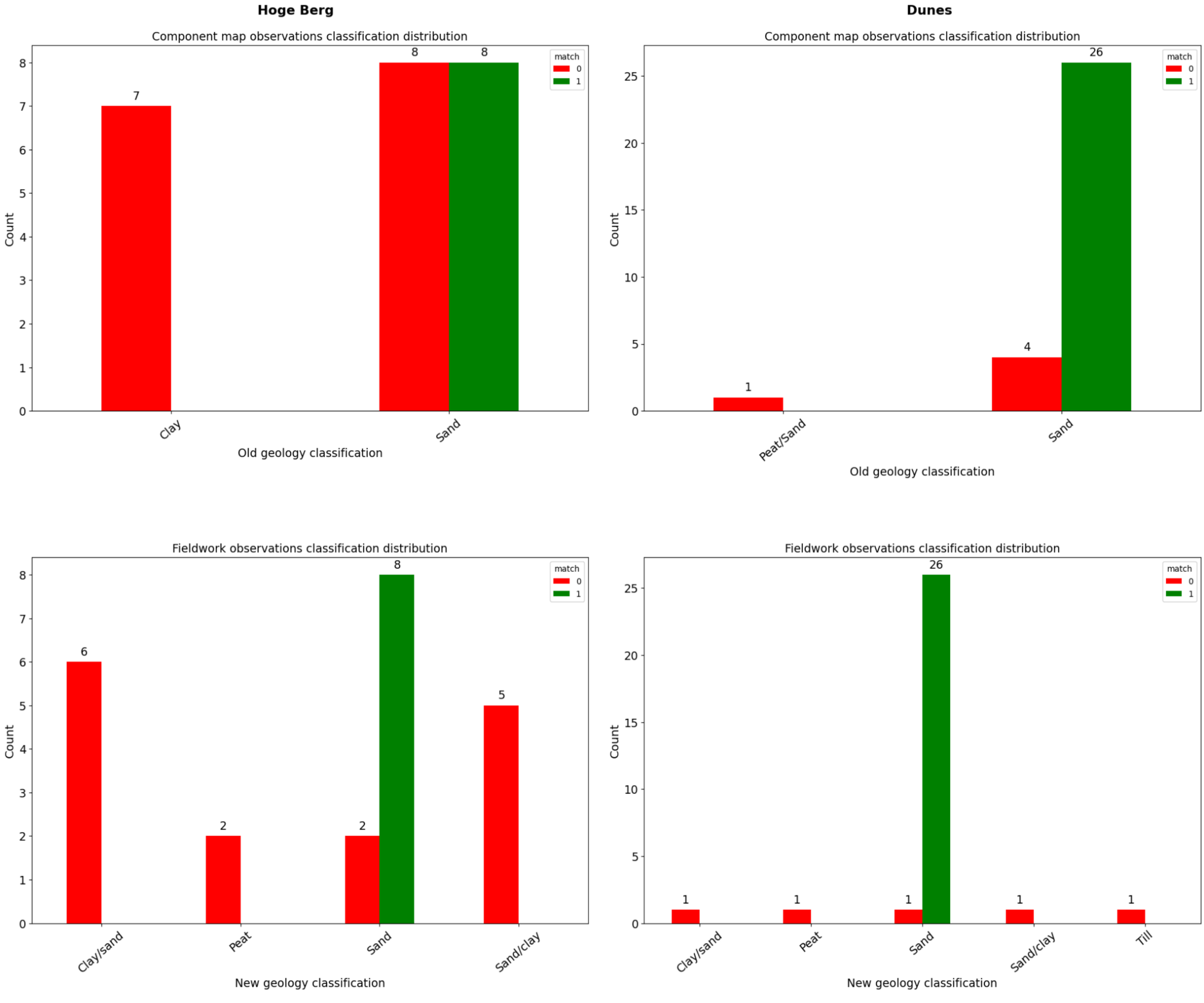

Figure 11.b: Detailed agreement counts per geological classifications for both case study areas

4.2 Geodiversity variety assessment

Figure 12 illustrates the percentage of total observations for each geomorphological class, comparing the field-based classifications (new) with the existing geomorphological map (old). Notably, in the dune area, five more geomorphological classifications were observed during the fieldwork that were not present in the existing classifications. In the ‘Hoge Berg’ area, less classes were observed during the fieldwork compared to the old geomorphological component map.

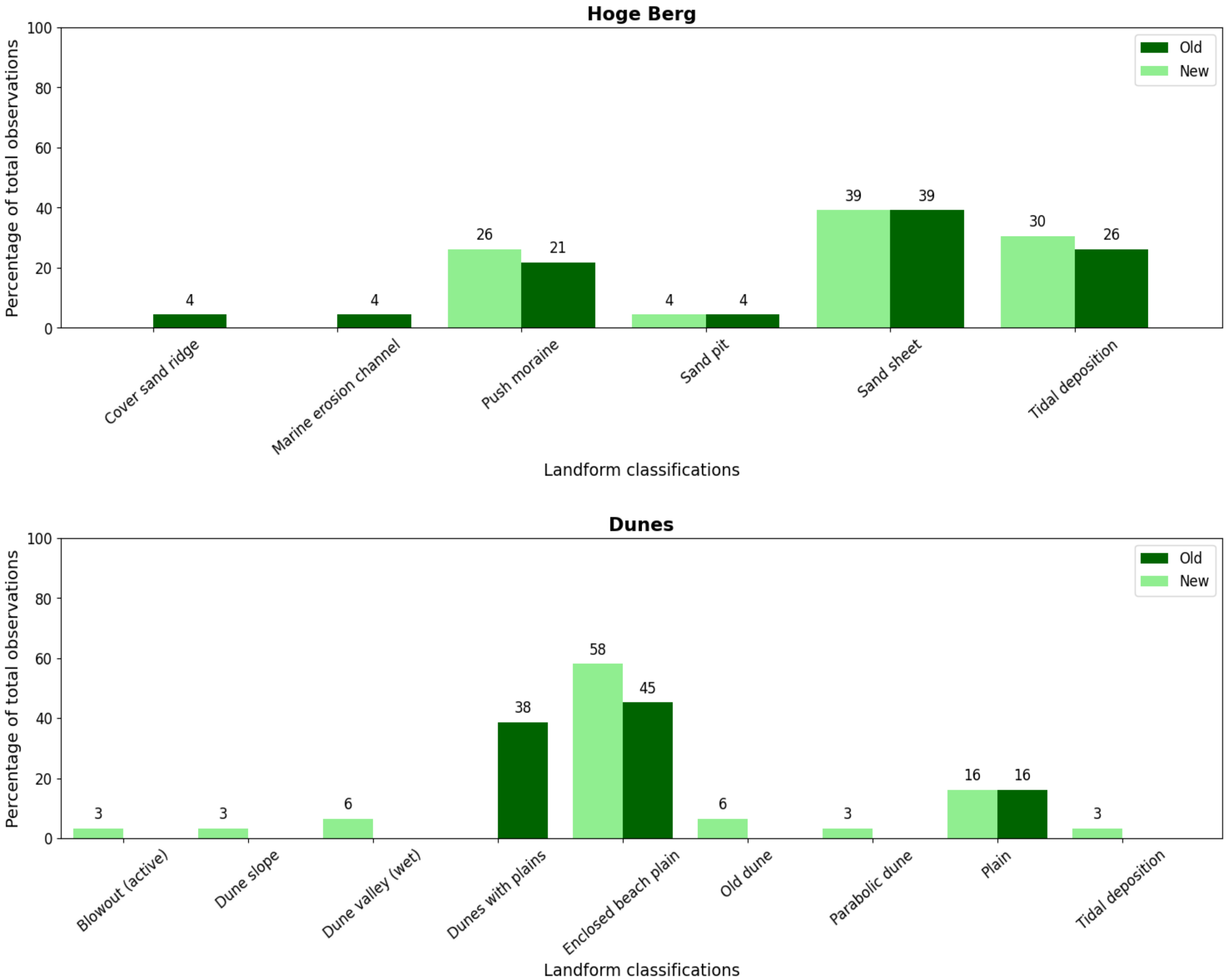

Figure 12: percentages of old and new geomorphological classifications per case study area

Figure 13 presents the percentage of total observations for each geological feature, comparing the field-based classifications (new) with the classifications from the geological component map (old). In both case study areas, sand is the predominant geology class. However, the correlation matrix (Figure 14) reveals that in the 'Hoge Berg', the texture is coarse in 9 out of 10 observations and fine in one observation. In contrast, in the dune area, the sand is coarse 18 out of 27 observations and fine in the remaining nine observations. This result indicates that the sand in the 'Hoge Berg' is predominantly coarse, while in the dunes, the sand varies between coarse and fine. Additionally, it is noteworthy that the new geological classifications in the 'Hoge Berg' are more evenly distributed compared to the dunes, where sand remains the dominant geological classification at 87%. The data suggests that the geological diversity is higher and more evenly spread in the 'Hoge Berg' case study area than in the dunes.

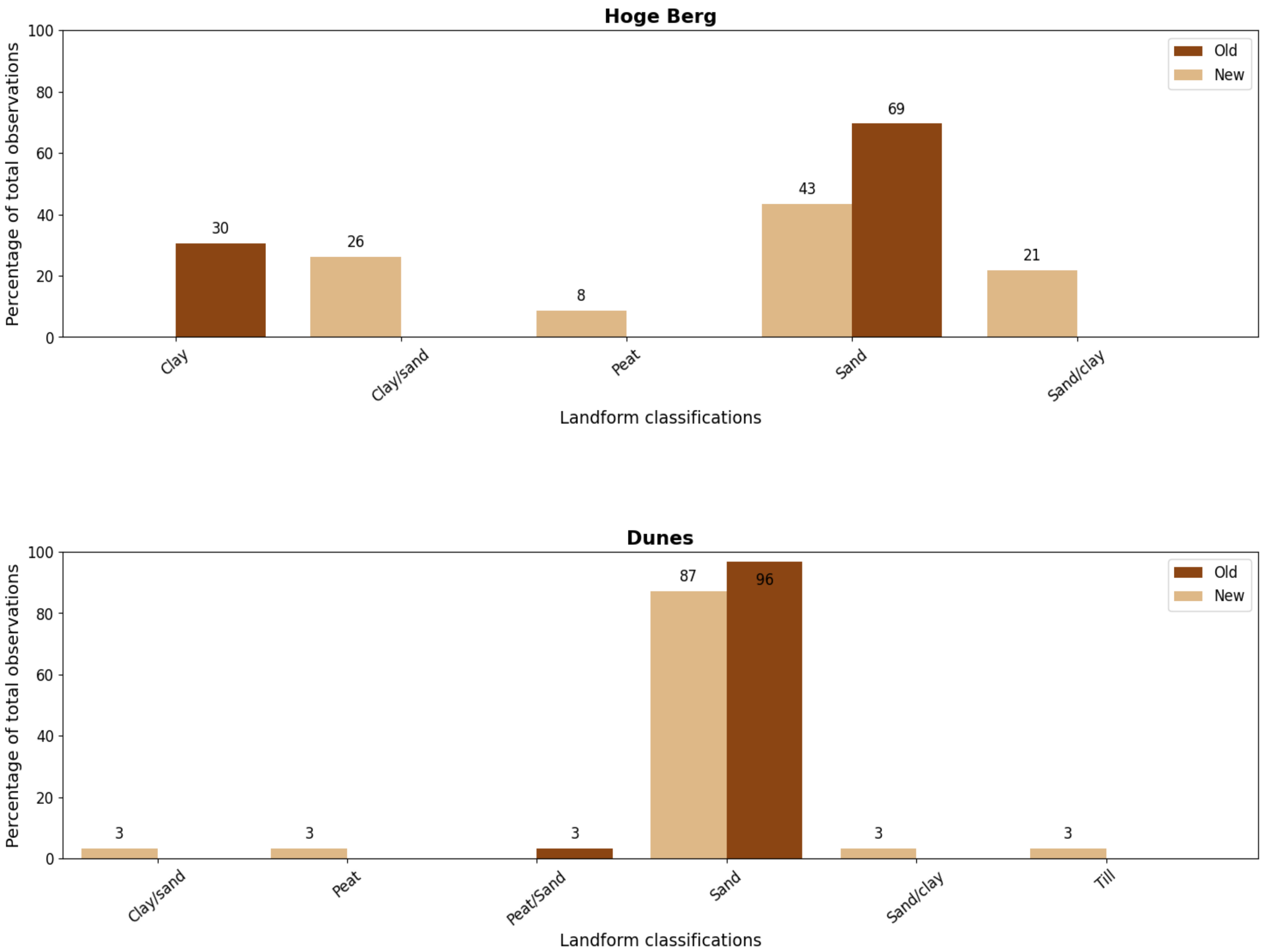

Figure 13: Percentages of old and new geological classifications per case study area

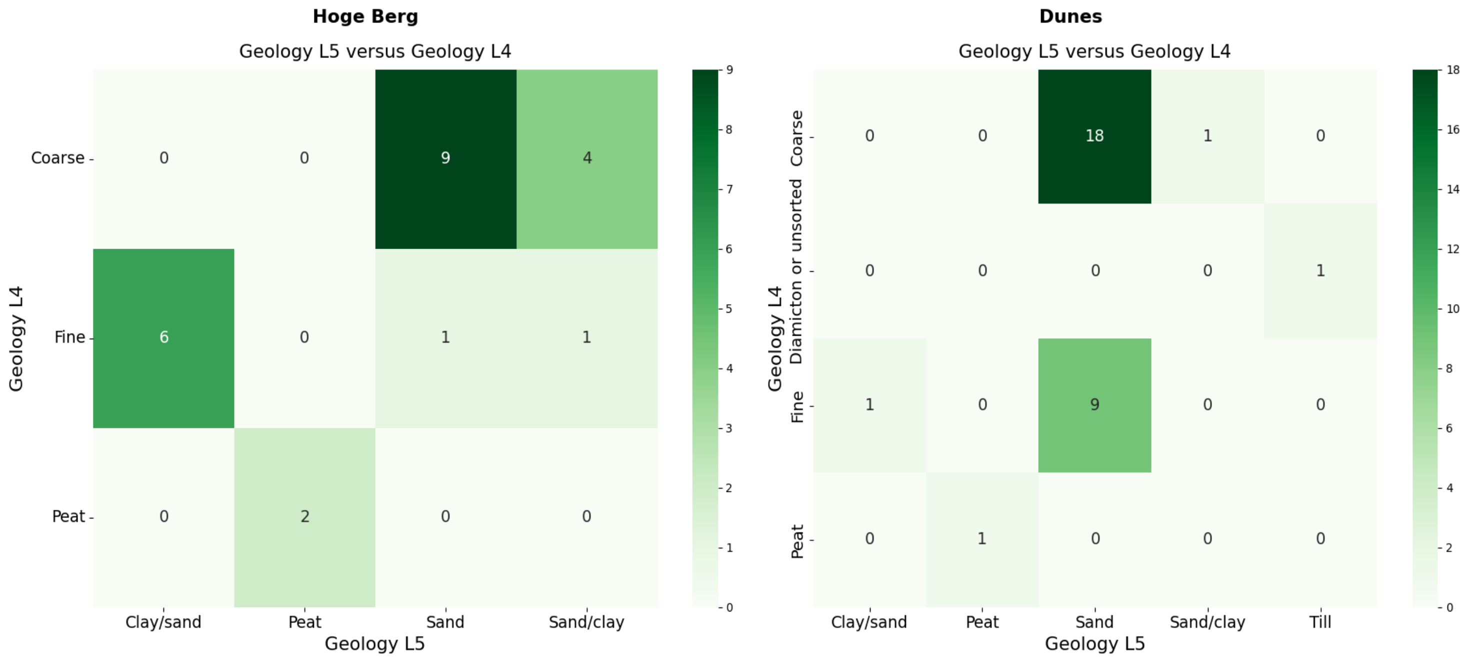

Figure 14: Correlation matrix that visualizes the relationship between geological features of the fourth and fifth taxonomic level per case study area. Each row represents a geological feature of the fourth taxonomic level and each

column represents a geological feature of the fifth level. The matrix should be interpreted as follows: The higher the number and thus the darker the color of the box, the higher the correlation. For example, in the 'Hoge Berg' area the level four geological feature fine is classified six times as clay/sand on the fifth level of the map, and once as sand and once as sand/clay.

Figure 15 visualizes the percentage of each organic soil content classification for both research areas. Notably, no predominant organic soils were found in the dune areas, whereas in the 'Hoge Berg' case study area, 7% of the soils were classified as organic. In the dunes, mineral and mixed soils were almost equally frequently identified, though mineral soils were identified 3% more often. In the 'Hoge Berg' case study area, mixed soil type is the most common.

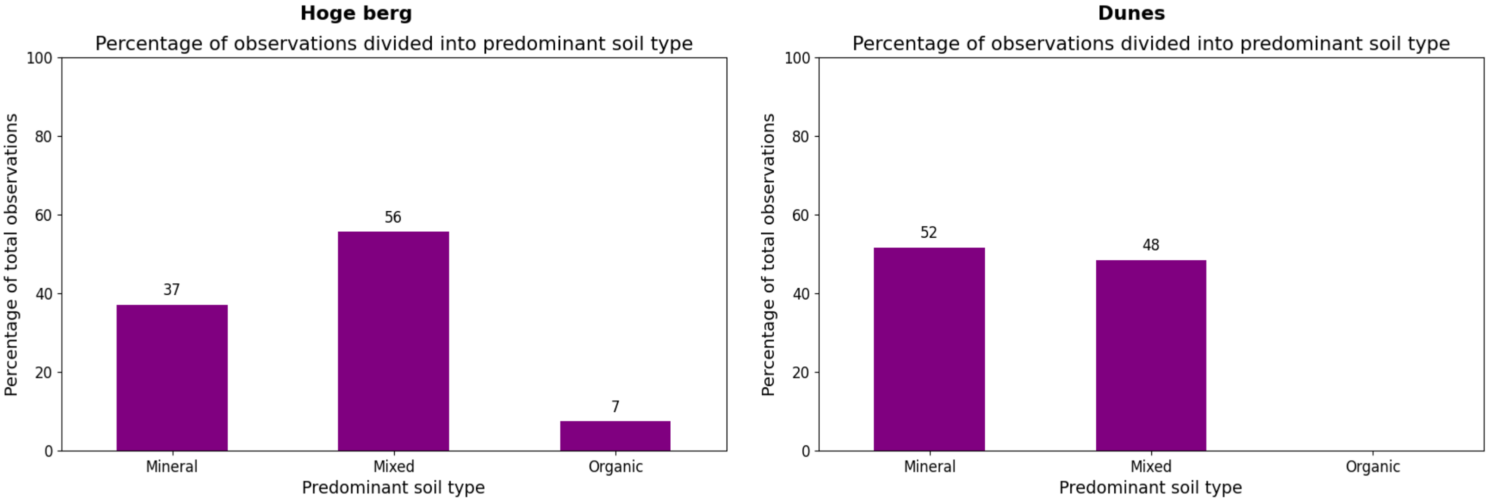

Figure 15: Percentages of the predominant soil classifications per case study area

5. Discussion

For the first time, a hierarchical geodiversity map has been created for two contrasting areas on Texel Island, based on a proposed taxonomy for global geodiversity mapping by Hjort et al. (2024). Three openly available and manually mapped components of geodiversity were successfully converted into a three-tier hierarchical digital map in ArcGIS Pro and agreement between field and map was determined. The results indicate that developing an effective workflow for this objective is achievable, although there are limitations to consider and possibilities for further improvement. The workflow routines and results will be discussed in this section. In particular, the choice of legend items and the geodiversity variety assessment process. Afterward, recommendations for future research will be discussed.

5.1 Workflow

The workflow of the mapping method was successful, as the routines were performed and the goals of developing and testing a hierarchical geodiversity map in Texel were achieved. This shows that the workflow is transparent and reproducible. It should be kept in mind that this methodological approach is explorative and open to future methodological improvements.

Data collection and field work

For the first routine, four openly available geodiversity component maps of the Netherlands were collected and clipped to the extent of Texel. The geodiversity taxonomy structure of Hjort et al. (2024) was implemented based on this data. Afterward, fieldwork was executed to test the geodiversity taxonomy in Texel and a hierarchical geodiversity map was created based on the newly acquired data.

The geomorphological and geological components of the geodiversity taxonomy as proposed by Hjort et al. (2024) were successfully applied to the extent of Texel whereas the soil and hydrological components were not. This was due to the discrepancy between the Dutch geodiversity maps and the geodiversity taxonomy regarding different definitions and classifications per geodiversity component. Therefore, more research and consensus are needed to close the discrepancy between Dutch geodiversity data and international geodiversity data. A general improvement of this method could be the inclusion of component maps with well-known and consistently used classification systems, but these are not available or lacking for the Dutch extent. It is advised that future research should make efforts to develop component maps with renowned classification systems for the Dutch extent.

Further detailed refinements for this method could include the use of more precise measurement equipment such as a hand auger could provide more insight into soil properties given that a hand auger can provide a deeper soil sample than a garden shovel. For the hydrological component, a pH test kit could be added to the research equipment to gain more insights into the water's chemical properties and a more detailed classification on the fifth taxonomic level could be made. Furthermore, the fieldwork allowed for a better understanding of the geofeatures present in both research areas. In the dune case study area, more soil samples were collected than in the 'Hoge Berg' area as the dune area had less restricted areas permitting a more comprehensive examination of the geodiversity components. The small sample size of approximately 30 samples per case study area should be expanded to enhance the statistical robustness of the findings. Additionally, the duration of the fieldwork can be expanded depending on the amount of samples needed and the technical difficulties of evaluating the research areas. In this method, three days for fieldwork was a limited time, given that all four geodiversity components need to be evaluated per sample point. Refinements to extend the fieldwork period would enable the collection of a larger number of samples and thus enhance the research's validity.

Visualization

In the results, levels 3-5 of the geodiversity taxonomy were utilized as these levels were necessary to map geodiversity hierarchically. The first taxonomic level entails the geodiversity component and the second level groups the component into broad classes, such as exogenic features or anthropogenic features. Both levels do not contain geofeatures that give interesting spatial information.

For the visualization of the hierarchical geodiversity map colorblind-friendly symbology was considered to make the map readable and usable to a wider range of users. Colorblind-friendly colors were chosen utilizing the ColorBrewer tool of Harrower & Brewer (2003) to visualize the geomorphological features of the map (Kilin 2022; Tol (z.d.)). Another visual cue to make multivariate maps readable for people with colorblindness is utilizing different shapes and sizes (Guha et al., 2022; Kilin, 2022) Therefore, the geological component features are visualized as a hatched pattern and differ in both colors, highlighting the material classification (i.e. sand, clay or gravel) and pattern width which emphasizes the material texture (fine, coarse or mixed). The soil features are presented with various colors of dots in the first-tier map and different sizes of hexagons in the second-tier map. The first-tier map has the lowest information density and limited use of color as only a few classifications are present at this scale, thus additional colors representing soil geofeatures are possible. Dots are chosen to delineate the soil classification as the shape of dots contrasts the uneven-colored shapes of the geomorphological polygons and the striped pattern of the geological components. However, as the second-tier map becomes more detailed and filled with more and smaller colored polygons, classifying the soil features with dotted colors is undesirable because it would make the map congested with colors and round shapes. Therefore, the soil geofeatures are classified with a colorless hexagon shape which differs in size to highlight the individual soil geofeature. In the third-tier of the geodiversity map, the visualization of soil features is absent as no classification equivalent to the highest geodiversity taxonomy has been made for the soil features.

Validation and analysis methods

To establish the validity of the produced hierarchical geodiversity map, an accuracy assessment was conducted. The accuracy assessment revealed that for the geomorphological component of the ‘Hoge Berg’ the accuracy was 87% whereas the accuracy in the dunes for the same geodiversity component was 61%. Conversely, the geological component accuracy was higher in the dune area at 84% compared to the ‘Hoge Berg’ area where it was 35%. In this accuracy method, information behind included data and classification is rather important for understanding the accuracy scores. For instance, the low geological agreement score in the ‘Hoge Berg’ can be explained by the fact that more detailed classes were added in the new geological classification of the ‘Hoge Berg’ research area. Notably, the geomorphological category ‘dunes with plains’ was consistently misclassified in the dune area, highlighting the need for more detailed classifications in the new geodiversity map.

The accuracy assessment, especially, the inconsistent accuracy scores in the ‘Hoge Berg’ area, indicates that the method used does not achieve reliable high accuracy scores as the obtained accuracy scores fall short of the desired accuracy level set by USGS for national maps, which aims for a minimum accuracy of 90% (U.S. Geological Survey, 1999). It should be kept in mind that the freely available component maps data was made with field observations and expert knowledge in a pre-digital era. Information on the component maps' accuracies is, in most cases, lacking, which also hampers a reliable assessment of the geodiversity assessment. The research methods by De Jong et al. (2021) and Hjort et al. (2024) did not yet suggest an accuracy to validate the hierarchical mapping method or the geodiversity taxonomy. Therefore, it should be noted that this accuracy assessment method is a first attempt towards assessing the accuracy of a hierarchical geodiversity map.

Similarly, the method of visualizing a hierarchical geodiversity map as described in Chapter 3 is a novel approach that has not been attempted before given that the taxonomy did not provide any methods for visualization. Further research is required to investigate whether the proposed visualization methods are appropriate for other research areas, as the map made for this thesis was focused on the specific features present on Texel.

5.2 Interpretation of results

The geodiversity map presents the distribution of geodiversity component features on Texel at taxonomic levels 3-5, demonstrating the successful integration of a geodiversity taxonomy to develop a hierarchical geodiversity map. The variety of geomorphological, geological, and soil features in both areas was analyzed based on in-field data observations and presented in section 4.3 of the results chapter.

Generally, the results suggest that the variety of geodiversity components is higher in the 'Hoge Berg' area than in the dune areas. This finding can be explained by the older geological age of the 'Hoge Berg' compared to the dune area. Research by Seijmonsbergen et al. (2018) and Zaitsev et al. (2012) suggests that increased landscape complexity is correlated with the geological age of the area. The older the geological age of an area, the more surface processes, such as soil formation and aeolian erosion, can contribute to greater landscape variation (Seijmonsbergen et al., 2018; Zaitsev et al., 2012).

Upon comparing the geomorphological classifications between both case study areas, it becomes evident that more new geomorphological classes were identified in the dune area compared to the 'Hoge Berg' study area. However, the existing classification in the geomorphological component map of the 'Hoge Berg' area includes more categories than observed during the fieldwork, resulting in a lower accuracy score for this component. Conversely, in the dune area, more geomorphological classes have been identified in the field compared to the component map. This difference can be attributed to the clearer visibility of geomorphological boundaries in the dune area's subsurface compared to the 'Hoge Berg' area, where these boundaries are obscured beneath the surface due to the older geological age and inactive landscape of the 'Hoge Berg' area.

The geology in the old component maps for both research areas was classified into two categories: sand and clay in the 'Hoge Berg' area, or sand and peat/clay in the dune area. During the fieldwork, more geological features were observed and thus added to the geodiversity map. These results indicate a higher variance in geological classifications than observed in the previous geological map. It should be noted that the variance in the 'Hoge Berg' case study area is divided more evenly compared to the dune area, where the category of sand (87%) is found substantially more than the other four categories (all 3%).

Another notable difference between the two case study areas pertains to the soil component of geodiversity. In the 'Hoge Berg', organic soils can be found, whereas, in the dunes, the soils are predominantly mixed or mineral soils. This data supports the theory that dune areas lack organic soils due to insufficient organic material accumulation and limited soil development, aligning with research presented by Kammann et al. (2022) and Maun (2009).

Finding a higher and more evenly distributed number of geodiversity classifications in the 'Hoge Berg' research area compared to the dune area is in line with research by Hjort and Luoto (2010), which indicated that high geodiversity areas often reflect heterogeneous abiotic conditions where erosion and deposition processes are significant in landscape development. This is the case for the 'Hoge Berg' and less so for the dune area.

5.3 Future research

The recommendations for further research are threefold and pertain to improving the mapping methodology, exploring the method's scalability, and enhancing the geodiversity database.
First, to improve the completeness and accuracy of the mapping method it would be beneficial to include more geodiversity classes. This could be achieved by gathering more field data and utilizing LiDAR data, as done by De Jong et al. (2021). For the Texel study area, more specific soil and hydrological classifications in line with a global geodiversity taxonomy should be included. More research is needed to make such soil and hydrological classifications since this type of data is not yet available in the Netherlands.
The second recommendation pertains to exploring the scalability of the method. Since this method utilizes a global geodiversity taxonomy adjustable to different research areas, it has the potential to be expanded to a larger scale, such as the Netherlands. Scaling up requires redesigning the experimental design to accommodate broader spatial extents and varying geodiversity features. To test this scalability, it is recommended to begin by applying the methodology to a slightly larger area than Texel in an exploratory research design. Utilizing students to collect data and conduct research analyses could be a cost-effective approach. If initial findings are promising, then the research can be expanded to a nationwide scale where more time and resources need to be invested. Accurate and standardized data on the third, fourth, and fifth levels of the geodiversity taxonomy is necessary to scale up this method as it will facilitate consistent and comparable geodiversity maps. It should be kept in mind that levels three and four are more achievable to research as these features are often easily visible and do not require additional assessments. Documenting and evaluating geofeatures of the fifth level will require more effort and resources.
Last, the third recommendation concerns the availability of global geodiversity data. Efforts should be taken to create standardized geodiversity features databases on both national and international scales to facilitate comparison between areas of interest. Currently, the lack of standardized geodiversity data poses a significant challenge to the interoperability between geodiversity studies (Hjort et al., 2024; Wolniewicz, 2023; J. Ibáñez & Brevik, 2019). Standardized databases would enable a more uniform approach to data collection, classification, and analysis, ensuring that geodiversity features are consistently documented and interpreted. This could be achieved by developing a set of common protocols and guidelines for data collection and classification that align with a global geodiversity taxonomy. A consensus is necessary regarding the types of data to be collected, the methodologies for collecting these data, and the analytical methods (Hjort et al., 2024; Wolniewicz, 2023; J. Ibáñez & Brevik, 2019)

6. Conclusion

This research has yielded valuable insights into the visualization and distribution of geodiversity features in Texel. Reflecting on the findings of this research, it can be concluded that the developed method offers a systematic approach utilizing a geodiversity taxonomy to map geodiversity while providing information on various scales. From the taxonomic levels proposed by Hjort et al. (2024), only the third, fourth, and fifth levels have practical importance when geodiversity is displayed spatially. The geofeature groups from level three offer a first impression of the environments on a supra-regional scale and correlate to Tier 1 of the hierarchical mapping method. Tier 2 shows the distribution of the geofeature subgroups and offers detailed information for application on a regional scale. The Tier 3 map is based on the fifth taxonomic level of geofeatures and provides the highest detail map suitable for application on a local scale. The hierarchical structure allows for detailed local assessments and broader regional analyses utilizing a single map layer, enhancing the understanding of landscape dynamics. Utilizing colorblind-friendly colors and different shapes and sizes enhances the readability and usability of the hierarchical geodiversity map for people with color-vision impairment. Furthermore, the geodiversity variety assessment results indicate that more detailed classifications can be added to the existing geodiversity component maps of the Netherlands. The geomorphological classes in the 'Hoge Berg' research area are mainly sand sheet, tidal deposition, and push moraine. The main geomorphological class in the dune area is the enclosed beach plain. The main geological classes present in the 'Hoge Berg' area are sand and clay while in the dunes it is mainly sand. These findings highlight the importance of developing hierarchical geodiversity maps to better understand landscape diversity. Future research should focus on expanding the research extent of the hierarchical mapping method and improving the accuracy of the geodiversity map. Finally, efforts should be taken to create standardized geodiversity features databases on national and international scales to facilitate comparison between areas of interest.

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Appendices

Appendix A
Data collection and preparation

A.1 Field work form

This field form will be used to structure and unify the in-field observations during the fieldwork in Texel.
The first column states the variables per observation point. These variables are categorized into the four main geodiversity components and then even further classified into five different taxonomy levels, as proposed by Hjort et al. (2024). Furthermore, designated rows for additional comments on unique details that are not encapsulated in the taxonomy have been added per component. Additionally, GIS codes, based on the Texel classification scheme designed for this research, per component can be added for every observation point. Finally, photos can be added to the last row to specify and depict certain findings.

Observation number (n)	1	n+1
Date		
Coordinates		
Component (L1)	Geomorphology	
Geofeature (GF) class (L2)		
Process: GF group (L3)		
Detail Process: GF subgroup (L4)		
Landform: GF (L5)		
Geom comment		
GIS code		
Component (L1)	Geology	
GF class (L2)		
GF group (L3)		
GF subgroup (L4)		
Additional detail: GF (L5)		
Parent material		
Geo comment		
GIS code		
Component (L1)	Soil	

GF class (L2)		
GF group (L3)		
Soil type: GF subgroup (L4)		
Additional details: GF (L5)		
Soil comment		
GIS code		
Component (L1)	Hydrology	
GF class (L2)		
GF group (L3)		
GF subgroup (L4)		
Additional details: GF (L5)		
Hydro comment		
GIS code		
Photos		

A.2 Geodiversity taxonomy of Hjort changed for application on Texel

Geomorphology

L1_Component	L2_Geofeature class	L3_Geofeature group	L4_Geofeature subgroup	L5_Geofeature
A: Geomorphology	endogenic features (1000)	tectonic	fold	symmetrical / asymmetrical / isoclinal /
			fault	normal / reverse / strike-slip / oblique /
		volcanic	depression	crater / caldera / maar /
			cone	stratovolcano / ash cone / cinder cone /
			dome	cumulo-volcano / shield-volcano /
			lava and tephra	lava flow / block lava (aa lava) /
			other volcanic	longitudinal dyke / annular dyke /
		plutonic (1100)	bodies and masses	stock / laccolith / lapolith / phacolith /
			crack filling (1110)	dike / sill /
	features exogenic (2000)	weathering (2100)	chemical (2110)	indicators of solution / carbonation /
			physical (2120)	indicators of frost / thermal stress /
			biological (2130)	indicators of plant (roots) / animal /
		mass movements (2200)	falls	rock fall / boulder fall / debris fall /
			topples	rock block topple / rock flexural topple /
			slides	rock rotational slide / rock planar slide /
			flows (2210)	soil creep / frost creep / earth flow /
			lateral spreads	rock slope spread / liquefaction spread /
		erosion (2300)	glacig.-glacif.-glacil.-glacim. (2310)	cirque / U- and hanging valley /
			marine (2320)	turbidity current channel / gully /
			lacustrine (2330)	turbidity current channel / gully /
			aeolian (2340)	deflation surface / desert pavement /
			fluvial-alluvial (2350)	sheet erosion / rill / gully / ravine /
			littoral	chasms / cut bank or cliff / notch /
			nival (2360)	nivation hollow / nivation terrace /
			biotic (2370)	cliff / pit / tunnel / linear depression /
		deposition (2400)	glacig.-glacif.-glacil.-glacim. (2410)	drumlin / lateral moraine /
			marine (2420)	organic reef / fringing reef /
			lacustrine (2430)	turbidity current deposits /
			aeolian (2440)	sand sheet / sand ramp / sand sea /
			fluvial-alluvial (2450)	alluvial fan / fan piedmont / bar /
			littoral (2460)	beach / bar / barrier / spit and hook /
			organic (2470)	hummock / ridge or string / peat plain /
			nival (2480)	nivation ridge / nivation platform /
			biotic (2490)	hummock / tower / ridge / terrace /
	extraterrestrial features	cryogenic	cryoturbation and ground frost	frost heaved block / earth hummock /
			aggradation of ground ice	ice-wedge / other vein ice /
			degradation of ground ice	thermokarst depression /
		meteorite	depression	simple craters / complex craters / basins /
			crests	flat-topped / thin / rounded / complex /
			ejecta	ejecta blanket /

Soil

L1_Component	L2_Geofeature class	L3_Geofeature group	L4_Geofeature subgroup	L5_Geofeature
C: Soils	mineral (1000)	strong human influence (1100)	anthrosols (1110)	hydragric / hortic / pretic / gleyic / stagnic /
			technosols (1120)	ekranic / linic / urbic / spolic / garbic /
		limited root growth (1200)	cryosols (1210)	glacic / turbic / subaquatic / reductaquic / leptic /
			leptosols (1220)	nudilithic / coarsic / skeletic / subaquatic / histic /
			solonetz (1230)	abruptic / gleyic / stagnic / mollic / salic /
			vertisols (1240)	salic / sodic / leptic / petroduric / gypsic /
			solonchaks (1250)	petrosalic / gleyic / stagnic / sodic / petrogypsic /
		characteristic Fe/Al chemistry (1300)	gleysols (1310)	thionic / reductic / subaquatic / hydragric / irragric /
			andosols (1320)	aluandic / vitric / leptic / hydragric / gleyic /
			podzols (1330)	ortsteinic / carbic / albic / leptic / hortic /
			plinthosols (1340)	petric / pisoplinthic / gibbsic / stagnic / geric /
			planosols (1350)	reductic / thionic / leptic / hydragric / irragric /
			stagnosols (1360)	reductic / thionic / leptic / hydragric / irragric /
			nitisols (1370)	ferralic / ferritic / leptic / rhodic / geric /
			ferralsols (1380)	ferritic / gibbsic / rhodic / geric / nitic /
		soluble salt or non-saline substance accumulation (1400)	durisols (1410)	petric / petrogypsic / gypsic / petrocalcic / calcic /
			gypsisols (1420)	petric / petrocalcic / calcic / leptic / gleyic /
			calcisols (1430)	petric / leptic / gleyic / stagnic / lixic /
		clay-enriched subsoil (1500)	retisols (1510)	abruptic / fragic / glossic / leptic / plaggic /
			acrisols (1520)	abruptic / fragic / leptic / hydragric / pretic /
			lixisols (1530)	abruptic / fragic / petrocalcio / leptic / hydragric /
			alisols (1540)	abruptic / fragic / leptic / hydragric / plaggic /
			luvisols (1550)	abruptic / fragic / petrocalcic / leptic / hydragric /
		little or no profile differentiation (1600)	cambisols (1610)	fragic / thionic / hydragric / irragric / terric /
			fluvisols (1620)	tidalic / pantofluvic / orthofluvic / leptic / histic /
			arenosols (1630)	tidalic / aeolic / solimovic / tephric / tsitelic /
			regosols (1640)	tidalic / leptic / solimovic / aeolic / tephric /
	organic (2000)	thick organic layer (2100)	histosols (2110)	muusic / cryic / thionic / folic / floatic /
		rich organic topsoil (2200)	chernozems (2210)	petroduric / petrocalcic / leptic / hortic / gleyic /
			kastanozems (2220)	someric / petroduric / petrogypsic / gypsic / petrocalcic /
			phaeozems (2230)	rendzic / chernic / mulmic / petroduric / petrocalcic /
			umbrisols (2240)	hortic / terric / chernic / mulmic / fragic /

Hydrology

L1: Component	L2: Geofeature class	L3: Geofeature group	L4: Geofeature subgroup	L5: Geofeature
D: Hydrology	surface water (1000)	ocean or sea (1100)	high salinity (1110)	<0°C / 0-5°C / 25-30°C/>30°C
			medium salinity (1120)	<0°C / 0-5°C / 25-30°C/>30°C
			low salinity (1130)	<0°C / 0-5°C / / 25-30°C/>30°C
		standing water (1200)	saline lake (1210)	ultra oligotrophic / oligotrophic / mesotrophic /
			brackish water (1220)	ultra oligotrophic / oligotrophic / mesotrophic /
			freshwater (1230)	ultra oligotrophic / oligotrophic / mesotrophic /
			ephemeral (1240)	ultra oligotrophic / oligotrophic / mesotrophic /
		running water (1300)	clear (1310)	laminar / turbulent / white water / pool /
			brown water (1320)	laminar / turbulent / white water / pool /
			turbid (1340)	laminar / turbulent / white water / pool /
			ephemeral (1350)	single / wandering / braided / discontinuous /
		frozen water	snow	cornice / snow drift / ripple marks / barchanoids /
			ice	sea ice / lake ice / ice cover on river / ice dam / icing /
		Spring	perennial	artesian / stream / seepage / pool / underwater /
			ephemeral	artesian / stream / seepage / pool / underwater /
	groundwater (2000)	subterranean waterbody	lake or pond	division based on chemical and/or physical property of water
			river or stream	division based on chemical and/or physical property of water
		unconfined aquifer (2100)	isotropic (2110)	division based on chemical and/or physical property of water
			anisotropic (2120)	division based on chemical and/or physical property of water
			fractured (2130)	division based on chemical and/or physical property of water
		confined aquifer (2200)	isotropic (2210)	division based on chemical and/or physical property of water
			anisotropic (2220)	division based on chemical and/or physical property of water
			fractured (2230)	division based on chemical and/or physical property of water
		perched groundwater (2300)	isotropic (2310)	division based on chemical and/or physical property of water
			anisotropic (2320)	division based on chemical and/or physical property of water
			fractured (2330)	division based on chemical and/or physical property of water
		confining groundwater layer (2400)	aquitard (2410)	division based on chemical and/or physical property of water
			aquiclude (2420)	division based on chemical and/or physical property of water
			aquifuge (2430)	division based on chemical and/or physical property of water

A.3 Conversion tables

Conversion table geomorphology

landform_subgroup_description	A_L5_Name	A_L4_Name	A_L3_Name	A_L2_Name	A_L5_GIS_Code	A_L4_GIS_Code
Kustduinen met bijbehorende vlakten en laagten	Dunes with plains	Aeolian	Deposition	Exogenic features	2442	2440
Dekzandrug	sand sheet	Aeolian	Deposition	Exogenic features	2441	2440
Stuifdijk	Dike	Crack filling	Plutonic	Endogenic features	1111	1110
Zeestrandglooiing	Beach ridge	Marine	Deposition	Exogenic features	2424	2420
Dekzandwelvingen	Sand shoal	Aeolian	Deposition	Exogenic features	2443	2430
Welvingen in getij-aanwassen	Curves in tidal accretions	Marine	Deposition	Exogenic features	2425	2420
Welvingen in getij-afzettingen	Curves in tidal deposits	Marine	Deposition	Exogenic features	2426	2420
Welvingen in zandplaten	Curves in sand banks	Marine	Erosion	Exogenic features	2321	2320
Laagte ontstaan door afgraving	Valley	Erosion	Erosion (Anthropogenic)	Anthropogenic features	3103	3100
Zee-erosielaagte	Plain	Marine	Erosion	Exogenic features	2322	2320
Klif	Cliff	Biotic	Erosion	Exogenic features	2361	2360
Stuwwal	Push moraine	Glacial	Deposition	Exogenic features	2411	2410
Groeve	Sand pit	Erosion	Erosion (Anthropogenic)	Anthropogenic features	3101	3100
Dalvormige laagte	Valley	Glacial	Erosion	Exogenic features	2311	2310
Getij-kreekbedding, zee-erosiegeul	Marine erosion channel	Marine	Erosion	Exogenic features	2323	2320
Vlakte van ten dele verspoelde dekzanden of löss	Löss cover	Aeolian	Deposition	Exogenic features	2444	2440
Ingesloten strandvlakte	Enclosed beach plain	Marine	Deposition	Exogenic features	2423	2420
Strandvlakte, zandplaat of slik	Beach plain	Marine	Deposition	Exogenic features	2427	2420
Vlakte van getij-afzettingen	Tidal deposition	Marine	Deposition	Exogenic features	2422	2420
Zeeboezemvlakte	Flood plain	Marine	Erosion	Exogenic features	2325	2320
Vlakte ontstaan door afgraving en/of egalisatie van duinen of strandwallen	Plain	Erosion	Erosion (Anthropogenic)	Anthropogenic features	3102	3100
Vlakte van mariene doorbraakafzettingen	Breach plain	Marine	Erosion	Exogenic features	2326	2320
Boezemland, vlietland, moerassige vlakte	Peat plain	Organic	Deposition	Exogenic features	2471	2470
Vlakte ontstaan door afgraving en/of egalisatie	Plain	Erosion	Erosion (Anthropogenic)	Anthropogenic features	3102	3100
Getij-oeverwal	Tidal levee	Marine	Deposition	Exogenic features	2428	2420
Gordeldekzandwelvingen	Belt sand curvatures	Aeolian	Deposition	Exogenic features	2445	2440
Gordeldekzandglooiing	Belt sand ridge	Aeolian	Deposition	Exogenic features	2446	2440
Storthopen met grind-, zand-, kleigaten of ijzerkuilen	Waste pit	Erosion	Erosion (Anthropogenic)	Anthropogenic features	3104	3100

Conversion table geological component

bodem1_oms	B_L5_Name	B_L4_Name	B_L3_Name	B_L2_Name	B_L5_GIS_Code	B_L4_GIS_Code	B_L3_GIS_Code	B_L2_GIS_Code
Vergraven	Sand	Mixed	Mechanical	Sediments and materials	1151	1150	1100	1000
Moeras	Peat	Peat	Organic	Sediments and materials	1210	1210	1200	2000
Oude bewoningsplaatsen	Sand	Mixed	Mechanical	Sediments and materials	1151	1150	1100	1000
Dijk	Clay/sand	Mixed	Mechanical	Sediments and materials	1152	1150	1100	1000
Afgegraven kleigronden	Clay	Fine	Mechanical	Sediments and materials	1143	1140	1100	1000
Bebouwing	Sand	Mixed	Mechanical	Sediments and materials	1151	1150	1100	1000
Kreekbeddingen	Clay	Fine	Mechanical	Sediments and materials	1143	1140	1100	1000
lemig fijn zand	Loamy sand	Fine	Mechanical	Sediments and materials	1144	1140	1100	1000
lichte zavel, profielverloop 5, of 5 en 2, of 2	Gravel	Coarse	Mechanical	Sediments and materials	1133	1130	1100	1000
zavel, profielverloop 3	Gravel	Coarse	Mechanical	Sediments and materials	1133	1130	1100	1000
leemarm en zwak lemig fijn zand	Sand	Fine	Mechanical	Sediments and materials	1141	1140	1100	1000
zavel en lichte klei, profielverloop 3	Gravel/clay	Coarse	Mechanical	Sediments and materials	1134	1130	1100	1000
zavel en lichte klei, profielverloop 4, of 4 en 3	Gravel/clay	Coarse	Mechanical	Sediments and materials	1134	1130	1100	1000
lichte zavel, profielverloop 2	Gravel	Coarse	Mechanical	Sediments and materials	1133	1130	1100	1000
matig fijn zand	Sand	Fine	Mechanical	Sediments and materials	1141	1140	1100	1000
lichte zavel, profielverloop 5	Grevel	Coarse	Mechanical	Sediments and materials	1133	1130	1100	1000
zware zavel, profielverloop 5	Clay	Fine	Mechanical	Sediments and materials	1143	1140	1100	1000
grof zand	Sand	Coarse	Mechanical	Sediments and materials	1131	1130	1100	1000
zeer fijn zand	Sand	Fine	Mechanical	Sediments and materials	1141	1140	1100	1000
matig fijn zand met ontkalkte bovengrond	Sand	Coarse	Mechanical	Sediments and materials	1131	1130	1100	1000
zavel, profielverloop 3, of 3 en 4, of 4	Gravel	Coarse	Mechanical	Sediments and materials	1133	1130	1100	1000
lichte zavel	Gravel	Coarse	Mechanical	Sediments and materials	1133	1130	1100	1000
zavel, profielverloop 2	Gravel	Coarse	Mechanical	Sediments and materials	1133	1130	1100	1000
zand beginnend ondieper dan 80 cm	Sand	Fine	Mechanical	Sediments and materials	1141	1140	1100	1000
zavel, profielverloop 3, of 3 en 4 of 4	Gravel	Coarse	Mechanical	Sediments and materials	1133	1130	1100	1000
klei, profielverloop 2	Clay	Fine	Mechanical	Sediments and materials	1143	1140	1100	1000
Moerige eerdgronden met een moerige bovengrond op zand	Peat/sand	Mixed	Mechanical	Sediments and materials	1153	1150	1100	1000
fijn zand	Sand	Fine	Mechanical	Sediments and materials	1141	1140	1100	1000
fijn zand met ontkalkte bovengrond	Sand	Fine	Mechanical	Sediments and materials	1141	1140	1100	1000
Moerige eerdgronden met een zanddek en een moerige tussenlaag op zand	Peat/sand	Mixed	Mechanical	Sediments and materials	1153	1150	1100	1000

Conversion table soil

bodem1_oms	C_L3_Name	C_L3_GIS_Code	C_L2_GF_Class	C_L2_GIS_Code
Vergraven	Young	2100	Mixed	2000
Moeras	Moderate	3200	Organic	3000
Oude bewoningsplaatsen	Young	2100	Mixed	2000
Dijk	Young	2100	Mixed	2000
Bebouwing	Young	1100	Mineral	1000
Kreekbeddingen	Moderate	1200	Mineral	1000
Hoge bruine enkeerdgronden	Young	3100	Organic	3000
Laarpodzolgronden	Old	1300	Mineral	1000
Tuineerdgronden	Moderate	2200	Mixed	2000
Knippige poldervaaggronden	Young	1100	Mineral	1000
Veldpodzolgronden	Old	1300	Mineral	1000
Knippoldervaaggronden	Young	2100	Mixed	2000
Beekeerdgronden	Young	1100	Mineral	1000
Vlakvaaggronden	Young	1100	Mineral	1000
Kalkrijke poldervaaggronden	Young	1100	Mineral	1000
Kalkhoudende vlakvaaggronden	Young	1100	Mineral	1000
Kalkarme poldervaaggronden	Young	1100	Mineral	1000
Kalkrijke nesvaaggronden	Young	1100	Mineral	1000
Gorsvaaggronden	Young	1100	Mineral	1000
Moerige eerdgronden met een moerige bovengrond op zand	Moderate	3200	Organic	3000
Gooreerdgronden	Moderate	1200	Mineral	1000
Kalkhoudende duinvaaggronden	Young	2100	Mixed	2000
Duinvaaggronden	Young	2100	Mixed	2000
Moerige eerdgronden met een zanddek en een moerige tussenlaag op zand	Moderate	3200	Organic	3000

Appendix B
Geodiversity taxonomy legend

Developed geodiversity taxonomy for the extent of Texel

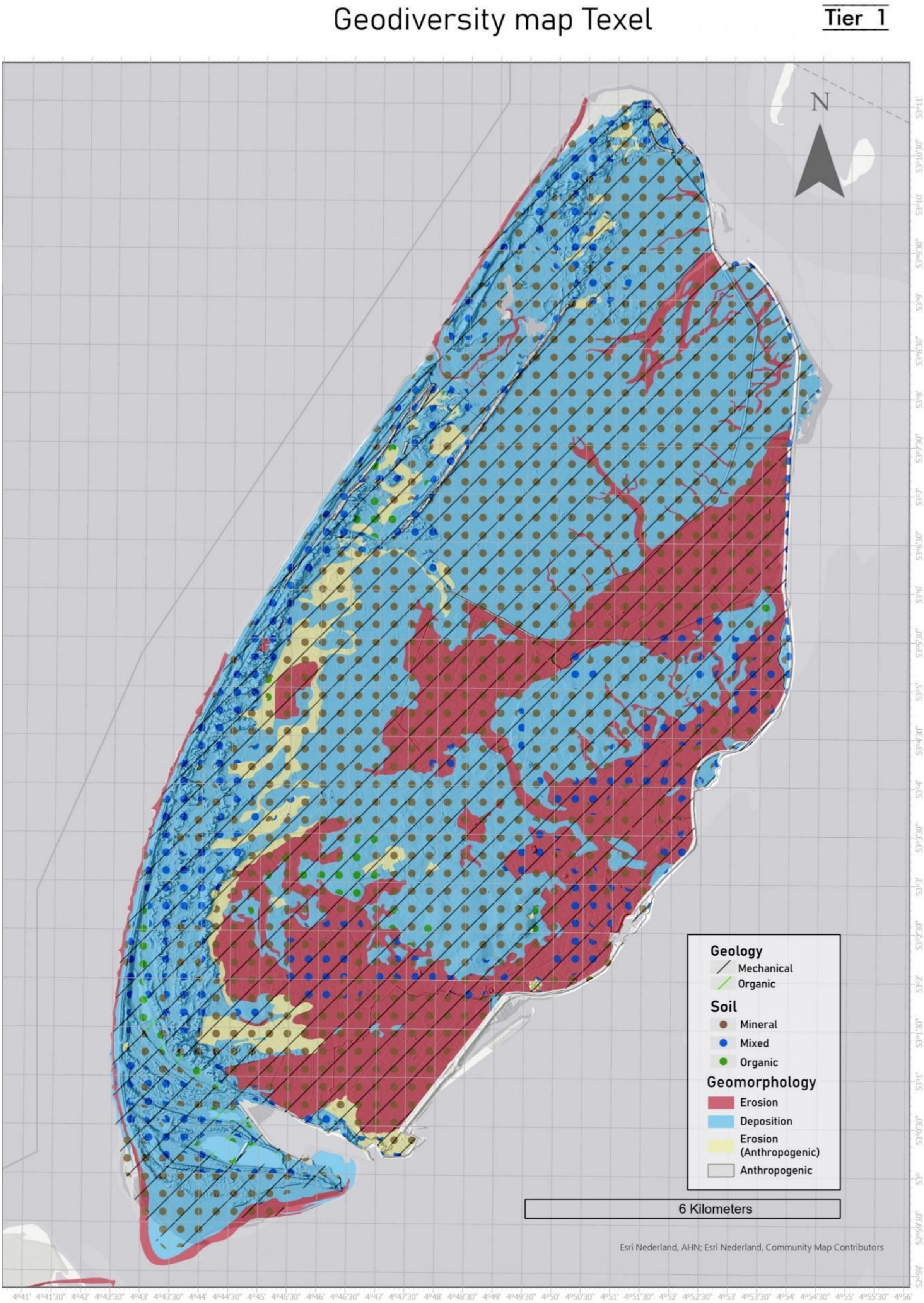
		Tier 1: Environments suggested scale range ≥ 30,001	**Tier 2: Process groups** suggested scale range 1:10,000 - 1:30,000	**Tier 3: Morphogenic domains** suggested scale range 1:2,500 - 1:10,000
L1 Component	L2 Geofeature class	**L3 Geofeature group**	**L4 Geofeature subgroup**	**L5 Geofeature**
A: Geomorphology	Exogenic features (1000)	Erosion (1100)	Glacial (1110)	Valley (1111)
			Marine (1120)	Curves in sand banks (1121)
				Plain (1122)
				Marine erosion channel (1123)
				Tidal plain (1124)
				Flood plain (1125)
				Breach plain (1126)
			Aeolian (1130)	Dune valley (1131)
				Dune slope (1132)
				Parabolic dunes (1133)
				Blowout (1134)
				Old dunes (1135)
			Biotic (1140)	Cliff (1141)
		Deposition (1200)	Glacial (1210)	Push moraine (1211)
			Marine (1220)	Sand sheet (1221)
				Tidal deposition (1122)
				Enclosed beach plain (1223)
				Beach ridge (1224)
				Curves in tidal accretions (1225)
				Curves in tidal deposits (1226)
				Beach plain (1227)
				Tidal levee (1228)
			Aeolian (1230)	Sand sheet (1231)
				Dunes with plains (1232)
				Sand shoal (1233)
				Löss cover (1234)
				Belt sand curvatures (1235)
				Belt sand ridge (1236)
			Organic (1240)	Peat plain (1241)
	Anthropogenic features (2000)	Erosion (2100)	Erosion (2110)	Sand pit (2111)
				Plain (2112)
				Valley (2113)
				Waste pit (2114)
		Anthopogenic (2200)	Anthropogenic (2210)	Dike (2211)
B: Geology	Sediments and materials (1000)	Mechanical (1100)	Diamicton or unsorted (1110)	till (1111)
			Coarse (1120)	Sand (1121)
				Sand/clay (1122)
				Gravel (1123)
				Gravel/clay (1124)
			Fine (1130)	Sand (1131)
				Clay/sand (1132)
				Clay (1133)
				Loamy sand (1134)
			Mixed (1140)	Sand (1141)
				Clay/sand (1142)
				Peat/sand (1143)
		Organic (1200)	Peat (1210)	Peat (1211)
C: Soil	Mineral (1000)	Young (1100)		
		Moderate (1200)		
		Old (1300)		
	Mixed (2000)	Young (2100)		
		Moderate (2200)		
		Old (2300)		
	Organic (3000)	Young (3100)		
		Moderate (3200)		
		Old (3300)		
	Mixed/Mineral (4000)	Young (4100)		
		Moderate (4200)		
		Old (4300)		
D: Hydrology	Surface water (1000)	Standing water (1100)	Ditch (1110)	
			Temporary water (1120)	
			Pond (1130)	

Appendix C
Mapping results

In depth explanation on the color visualization of the geomorphological component of the map:

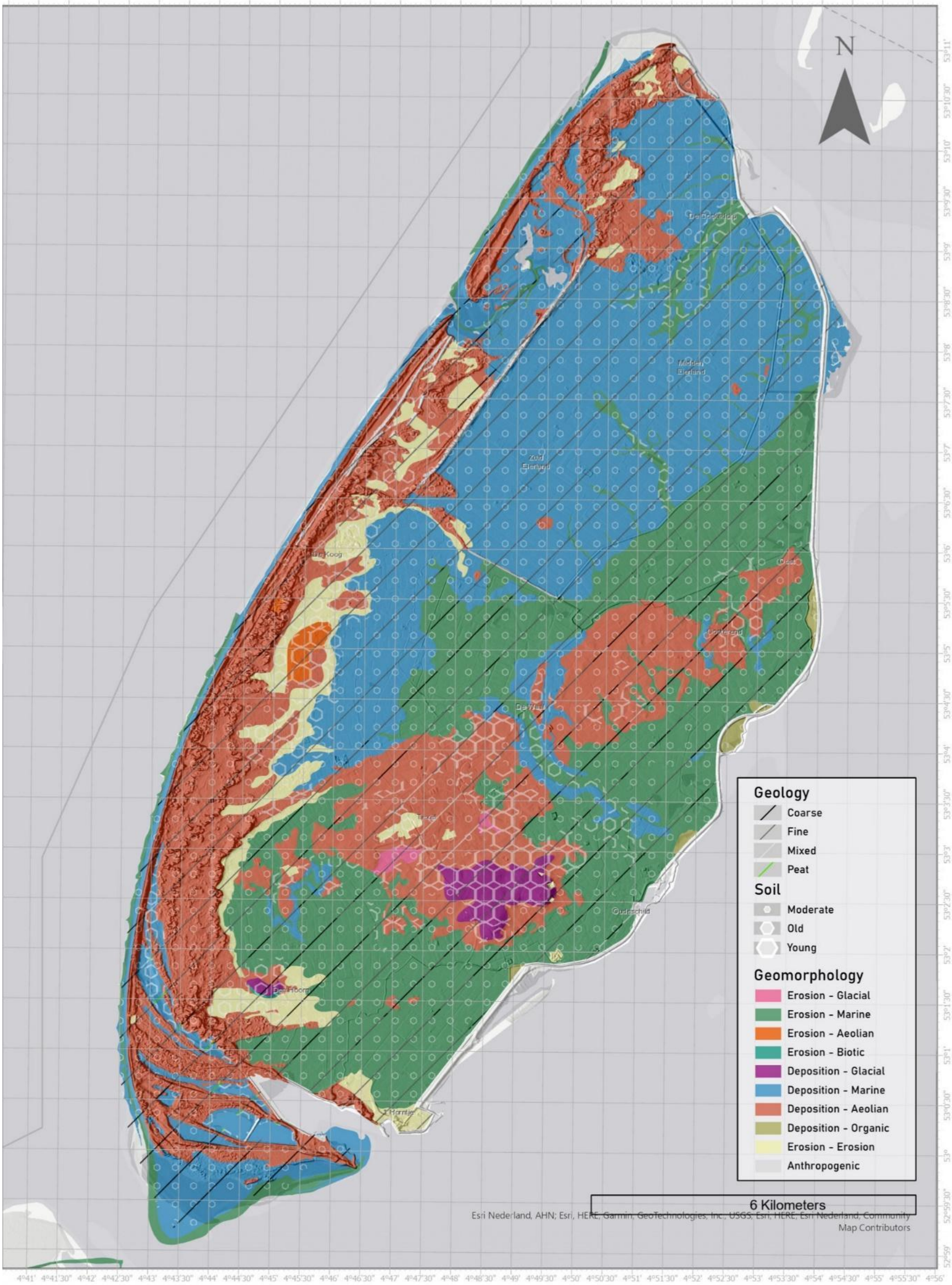
For the maps showing the first-tier of the geodiversity taxonomy, the classes of the geomorphology component are visualized in the colors pink for erosion features, blue for deposition features, yellow for anthropogenic erosion features and gray for anthropogenic features (Figure 8.a). The second-tier map subdivides these components further: pink (glacial), teal (marine), orange (aeolian), and turquoise (biotic) for erosion features; purple (glacial), blue (marine), red (aeolian), and olive (organic) for deposition features; and yellow for anthropogenic erosion and gray for the remaining anthropogenic features (Figure 8.b). In the third-tier geodiversity map, the fifth taxonomic classifications are subdivided into a hue color scheme based on the fourth level's base colors. The erosion marine features are visualized in a green hue color scheme whereas the erosion aeolian features are visualized in an orange hue color scheme. Deposition marine features are visualized in a blue hue color scheme and deposition aeolian features are featured in a red hue color scheme. The anthropogenic erosion classification corresponds with a yellow hue color scheme. For the glacial (valley (1111), push moraine (1211)), biotic (cliff (1141)) and organic (peat plain (1241))) features in the fifth level of the taxonomy, the color of the corresponding fourth level is used which is in this case pink, purple, turquoise and olive green. At last, the waste pit (2214) and dike (2211) are visualized in dark gray and black respectively (Figure 8.c).

C.1
Tier 1, 2 and 3 of the geodiversity map for the extent of Texel



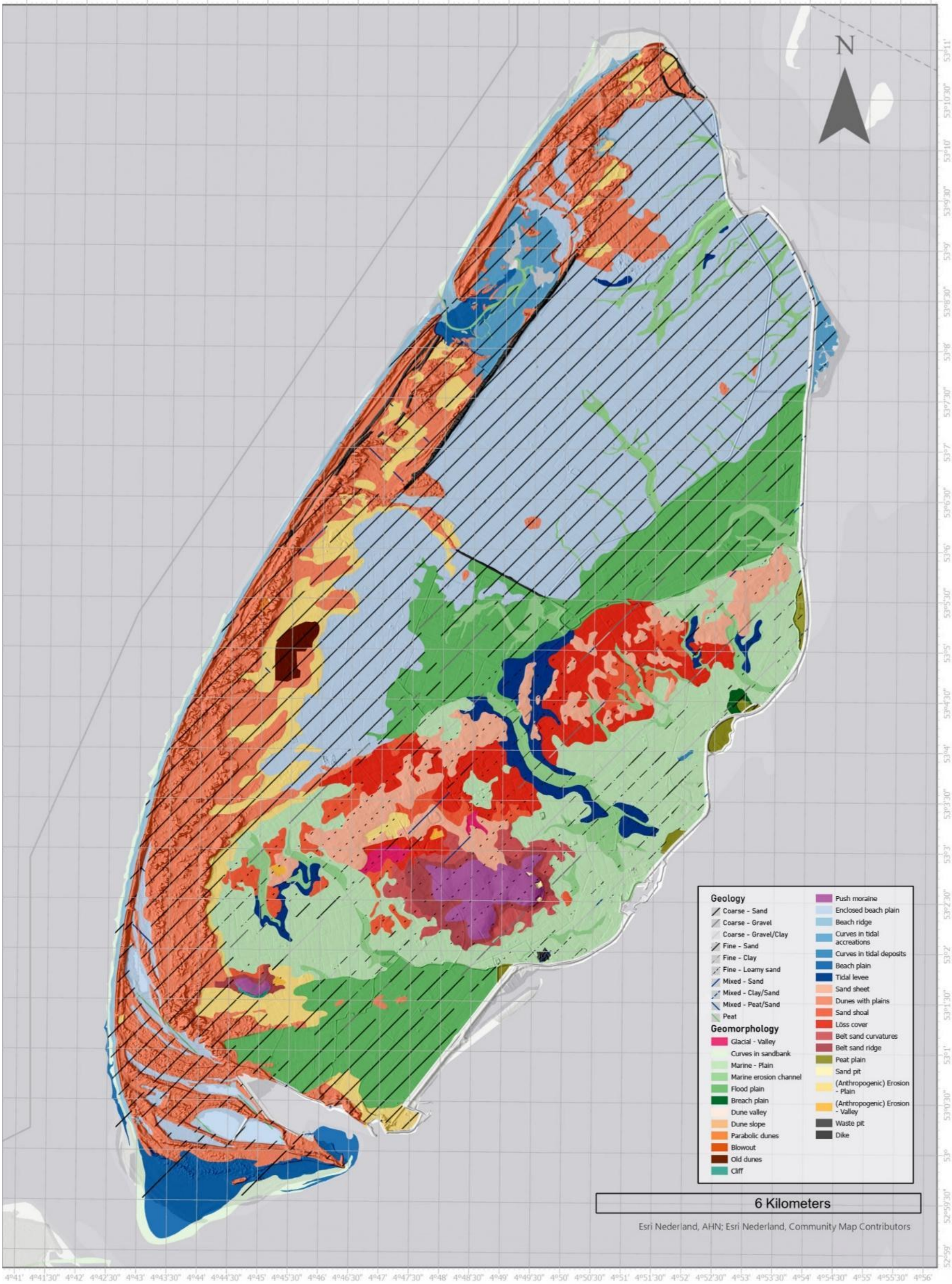
Geodiversity map Texel

Tier 2



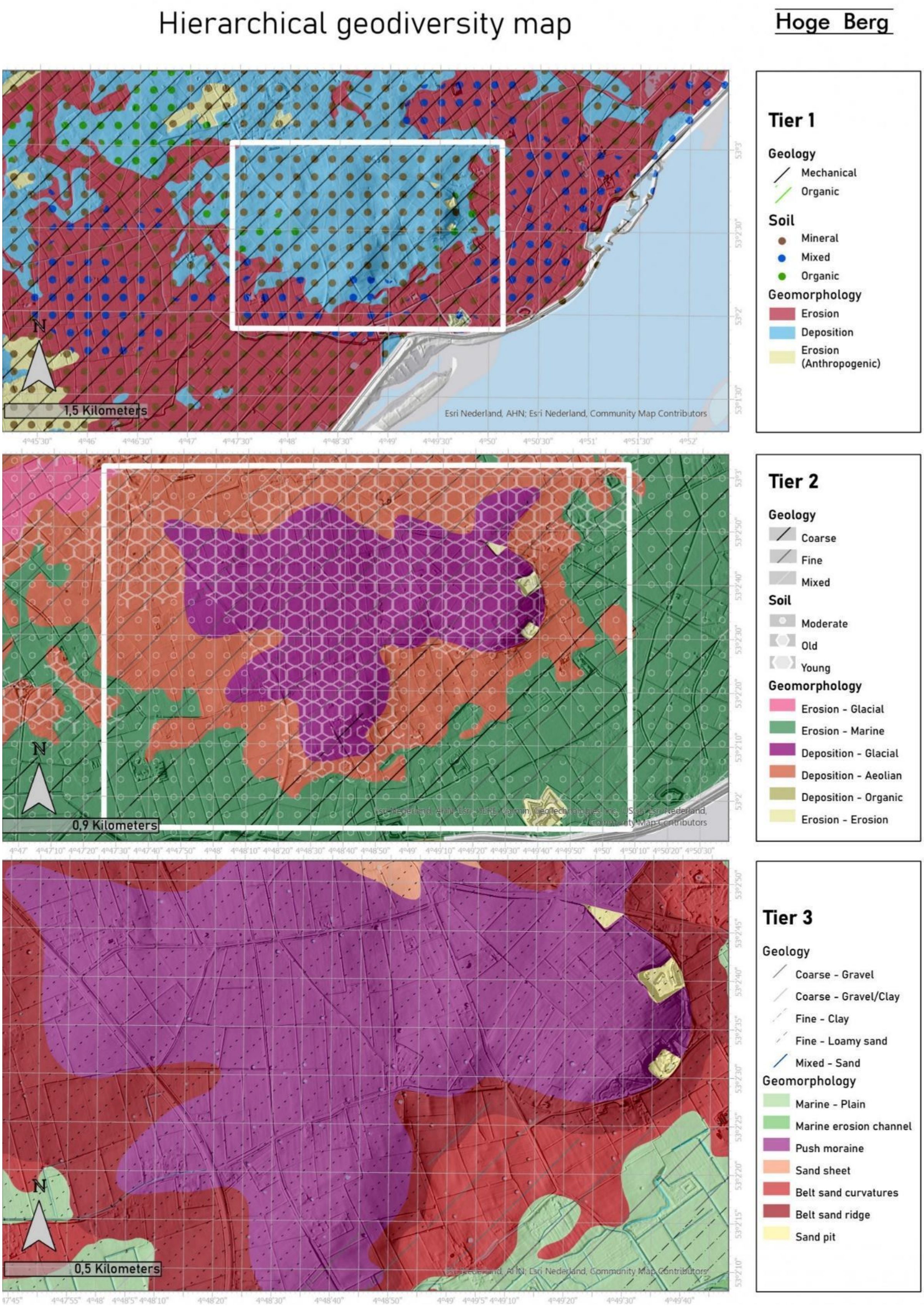
Geodiversity map Texel

Tier 3



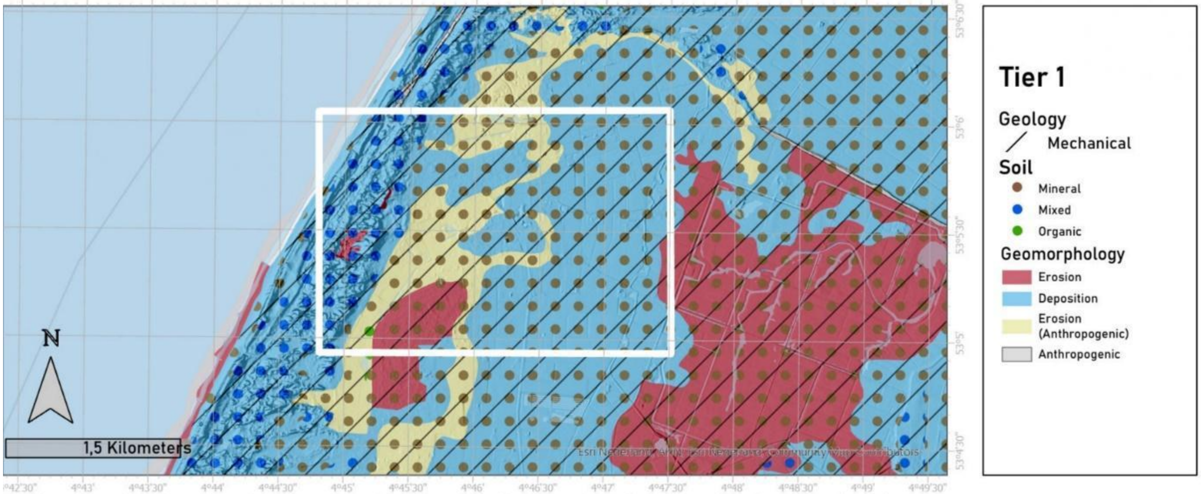
C.2

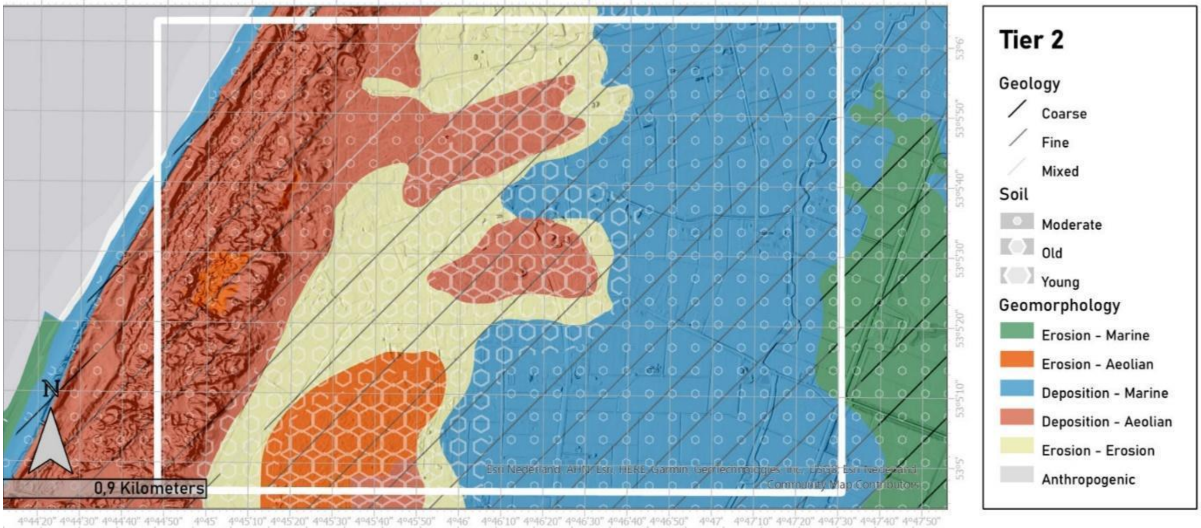
Tier 1, 2 and 3 for both case study areas: 'Hoge Berg' and dunes

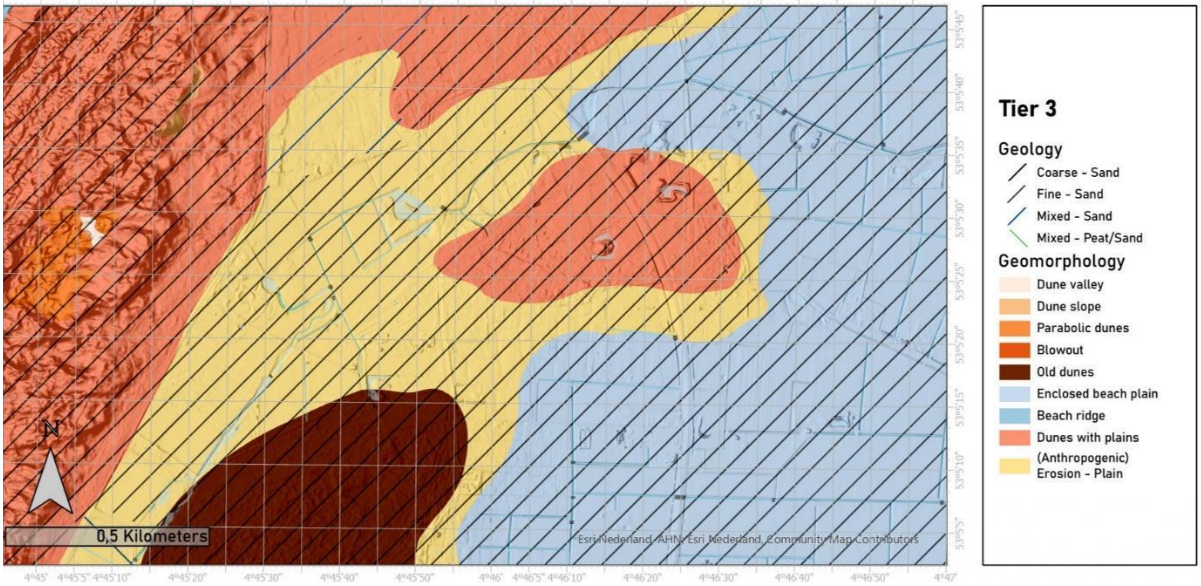


Hierarchical geodiversity map

Dunes







Appendix D
Data repository

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