



Geodiversity Assessment of French Guiana: Challenges and Implications for Sustainable Land Planning

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Received: 31 March 2022 / Accepted: 13 June 2022 / Published online: 29 June 2022

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Abstract

As operational concept, geodiversity implies a measurement and its application narrowed to a given spatial area, allowing the identification of clusters for prioritization and planning purposes. This study proposes a first geodiversity index assessment for French Guiana, a French Oversea territory located within the Guiana Shield (South America). Almost entirely covered by the Amazon rainforest associated with an exceptional biodiversity, French Guiana appears as an international conservation and land planning challenge facing multiple issues (e.g., urban, agricultural and industrial growth, forest management, mining planning). Geodiversity assessment is performed through a grid-based approach. A geodiversity index is calculated as the sum of four sub-indices (lithodiversity and unlithified diversity, mineral diversity, hydrodiversity, geomorphodiversity). The index calculation is based on the number of entities within each grid-cell. Spatial correlation is used to identify geodiversity clusters and finally the index is aggregated at different spatial units relevant for land planning (e.g., municipalities, hydrographic sectors, areas of ecological interest, the Guiana Amazonian Park, and the Departmental Mining Plan). The results show that the geodiversity index is mainly controlled by lithodiversity and that high geodiversity clusters are located along the gold-bearing greenstone belts crossing the territory. However, spatialized data concerning geodiversity are still inadequate or unavailable to perform proper operational assessments in French Guiana. Furthermore, based on qualitative examples, we discuss that the assessment of diversity alone might not be always enough for geoconservation nor land planning perspectives. It is pivotal to account for the geofunctionality—i.e., the contribution of geodiversity to the functioning of socio-ecological systems—and its interaction with anthropic activities.

Keywords Geodiversity · Quantitative assessment · Land planning · Ecosystem services · French Guiana

Introduction

As the abiotic equivalent to biodiversity, “geodiversity” is defined as the “the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms,

topography, physical processes), soil and hydrological features,” including “their assemblages, structures, systems and contributions to landscapes” (Gray 2013).

This concept was first introduced within geoconservation perspectives (Sharples 1995) and then to support land management actions (Nieto 2001). Such scientific trend highlights the role of abiotic resources as pivotal components of socio-ecological system functioning rather than simple supporting vehicles to natural diversity (Serrano and Ruiz-Flaño 2007; Van Ree et al. 2017; Brilha et al. 2018).

Nieto (2001) defines geodiversity as the number and variability of geological structures and materials within the boundaries of a given area under analysis, highlighting heuristic and operational purposes. This means, on one side, that the geodiversity concept implies the measurement of diversity, in terms, for instance, of richness and abundance. On the other hand, the assessment process must be site-specific, which means that it should be narrowed to a given study

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area to support context-specific conservation and planning actions (Jie et al. 2001; Brocx and Semeniuk 2007).

Zwoliński et al. (2018) review a wide range of methods to assess geodiversity and distinguish between qualitative methods (e.g., based on expert judgment, descriptive data, or on stakeholder's values) and quantitative methods (e.g., landscape metrics, map algebra, geodiversity indices). Among them, a geodiversity index has been initially proposed by Serrano and Ruiz-Flaño (2007) based on the relationship between a number of physical and geomorphological parameters of a given area. Pereira et al. (2013) have proposed a different method, which assesses a geodiversity index as the sum of partial numerical indices calculated over different thematic maps summing the geodiversity entities that occur in grid-cells.

Whatever the method used, geodiversity indices have been widely cited in the scientific literature to provide significant spatialized information for land planning purposes (e.g., Benito-Calvo et al. 2009; Araujo and Pereira 2018; Bétard and Peulvast 2019; Dias et al. 2021; Manosso et al. 2021; Vörös et al. 2021). Geodiversity can vary through space and time (Manosso et al. 2021) and, thus, its geovisualization plays a pivotal role for operational applications (Zwoliński et al. 2018). Therefore, the spatial associations between geodiversity values within a given area and their spatial patterns can be analyzed to support prioritization actions through the identification of high or low geodiversity clusters (Bétard and Peulvast 2019; Manosso et al. 2021). Spatial patterns can be assessed through global or local spatial autocorrelation statistics (Getis 2007) such as Anselin Local Moran's *I* which has been usually used to assess the spatial relationships between geodiversity and biodiversity. For instance, Manosso et al. (2021) assess geodiversity at the river basin scale through both landscape metrics and a geodiversity index and identify geodiversity clusters using Local Moran's index.

Finally, to support planning perspectives, geodiversity assessment should fit the scale and operational objectives fixed by decision-makers and stakeholders at given spatial extents. Such spatial extents might concern, for instance, administrative boundaries, water catchment management units, and sectorial planning frameworks (e.g., urban planning, forest management, mining planning). For instance, Malinowska and Szumacher (2013) assess geodiversity in Poland through landscape metrics according to different administrative units at the regional scale. Chrobak et al. (2021) use geomorphons as mesoregions to assess geodiversity and the geotouristic potential of the Western Carpathians region.

Overseas territories display often-important geo-ecological potentials for sustainable development and conservation strategies, while facing significant land planning and environmental management challenges. Among them, the

French Overseas territory of French Guiana is a sparsely populated territory (Le Tourneau 2020) and a high-biodiversity wilderness area (Galochet and Morel 2015) with one of the highest demographic growth rates in France (Millet 2018). Geological resources of French Guiana have been playing a pivotal role in the current and historical territorial dynamics of the region since centuries, mainly because of the presence of gold deposits (Scammacca et al. 2021; Jébrak et al. 2021). Indeed, georesources of French Guiana are the target of extraction (almost exclusively gold) and prospecting activities, such as for coltan (Gourcerol et al. 2019), but also of increasing conservation interest because of their geoheritage, paleontological, and archeological potentials and their links with biodiversity habitat support. Furthermore, urban sprawl, agriculture, and industrialization are increasing, highlighting the need of sustainable development and land planning strategies involving multiple human activities and drivers such as forestry, industry, mining, agriculture, tourism, and urbanization (Scammacca 2020). For such reasons, French Guiana is a major challenge for socio-ecological management, conservation, and sustainable land planning (Aubertin and Pons 2017). The acknowledgment and characterization of its geodiversity might support policy-making at the territory level in multiple fields (e.g., local water management, mining and urban planning, land-use and development strategies, tourism, and conservation).

Therefore, this article has the purpose to:

- i. Present the first quantitative assessment of French Guiana geodiversity and analyze geodiversity spatial patterns to identify clusters at the territory scale.
- ii. Estimate an average geodiversity index at different operational spatial aggregation units (e.g., municipalities, hydrographic sectors, areas of ecological interest, Guiana Amazonian Park, and the Departmental Mining Plan).
- iii. Identify and discuss the challenges of geodiversity assessment in French Guiana for land planning perspectives.

Materials and Methods

Socio-Geo-Ecological Settings of the Study Area

Currently, under equatorial climate, French Guiana is an Overseas European and French territory of approximately 84,000 km² located in South America, between Suriname and the North Region of Brazil (Fig. 1). With more than 95% of its surface covered by the Amazonian rainforest and a very dense hydrological network, this

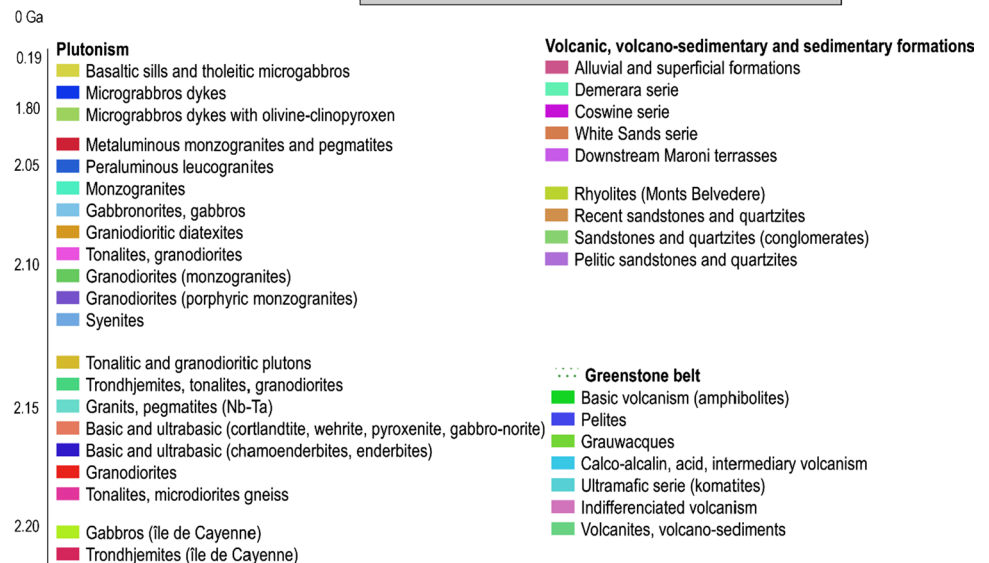
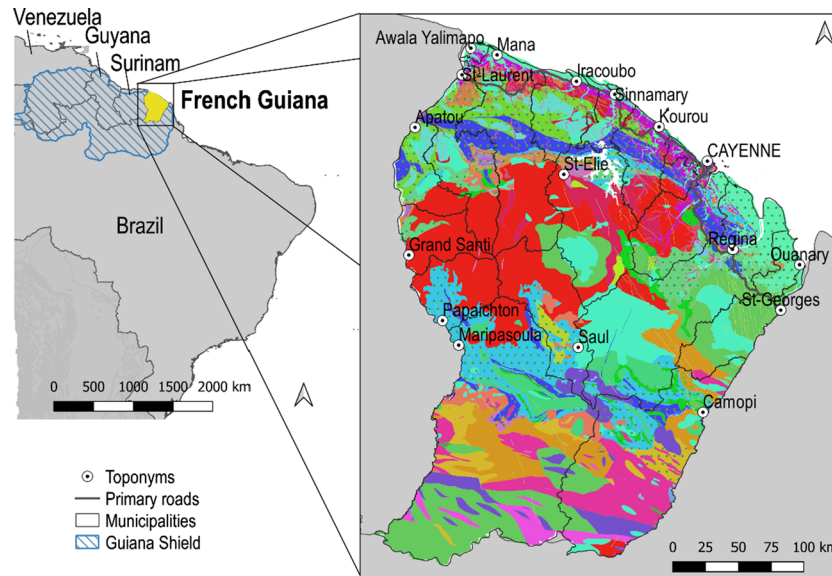
region is considered as a high-biodiversity wilderness area (Galochet and Morel 2015). French Guiana geology has been locally documented by the early works of the Overseas Scientific Research Office (Choubert 1949) and the French Geological Survey (BRGM) (Magnien et al. 1990). The geological history of the territory is well-described by the scientific literature (Vanderhaeghe et al. 1998; Delor et al. 2003; Milesi et al. 2003; Cassard et al. 2008; Cordani et al. 2009; Théveniaut et al. 2011) and it can be framed within the formation of the Guiana Shield, one of the three cratons of the South-American Plate and one of the major Precambrian terrains of Gondwanaland (Delor et al. 2003).

French Guiana geology can be divided within two main geomorphological domains: the uplands of the inner regions occupying 96% of the territory, with moderate relief energy (e.g., hills, multiple granitic inselbergs) reaching a maximum

of 850 m a.s.l., and the coastal plains of the lowlands (4% of the territory). The first domain is composed of outcrops of the oldest crystalline Paleoproterozoic basement mainly composed of magmatic and metamorphic rocks, while the second one is underlined by Quaternary sediments (Fig. 1). The Paleoproterozoic crystalline basement has been formed during the crustal growth of the Transamazonian orogeny (2.25–1.9 Ga) (Vanderhaeghe et al. 1998; Delor et al. 2003). Five main ensembles can be described:

- The greenstone belt, which includes two main units: (i) the Paramaca unit, mainly composed of volcanic lithology with greenschist to amphibolite facies metamorphism (i.e., metabasalts, meta-andesites, metadacites, and metarhyolites), and (ii) the Armina unit, which is mainly composed of poorly known metavolcanosedimentary rocks such as metapelites and metagreywackes.

Fig. 1 Location and geological map of the study area with the administrative boundaries and primary roads



- Three main granitoidic complexes: the Laussat and Tamoury Complex (2.18–2.16 Ga) is located in the north and south part of French Guiana. The Central Complex (2.15–2.13 Ga) is mainly composed of tonalite-trondhjemite-granodiorite and located in the central part of the territory. The late granitic complex (2.11–2.08 Ga) is located in the eastern part of the territory (e.g., Saint Georges).
- The Rosebel unit, which crops out in the northern part of French Guiana and is mainly composed of quartzites, metaconglomerate and, to a lesser extent, metapelites.
- The mafic and ultramafic massif (2.149–2.144 Ga), disseminated in the entire territory and composed of gabbro, gabbro, and granodiorite. Sometimes pyroxenolites and peridotites or serpentinites are also observed.
- Three series of basic dykes, which crosscut all the Paleoproterozoic units. The Apatoes series (0.198–0.189 Ga) mainly crops out in the eastern part of French Guiana. The Tampok (0.808 Ga) and the Comté series (1.8 Ga) are poorly represented in French Guiana. The Tampok dykes crop out in the southwestern part of the territory whereas the Comté series is mainly located in the central part.

Post-Jurassic events and weathering conditions contributed to the presence of lateritic paleosurfaces and thick soils over most of the region, between the lithological units and the biosphere (e.g., saprolites, iron-rich crusts, laterites; Théveniaut and Freyssinet 2002). During the Quaternary, sea level variations led to the development of two main fluvio-marine units forming the ancient and recent coastal plains. The oldest one (Zanderij formation) is of Pleistocene age whereas the Cosvine and the Démérara formations are from Holocene, the latter one being richer in silts and clays transported by the Amazon River.

Guyana literally means “land of many waters” (Clifford 2011) and, indeed, hydrologic resources are divided in groundwater bodies (84,000 km² in confined aquifers) and a highly dense and tufted network of surface water bodies (almost 20,000 km of length) spread across the territory (Barret 2001; DEAL 2013). The only plain surface water body is the *Petit-Saut* hydroelectric dam reservoir (Pestana et al. 2019).

Human occupation of French Guiana reflects its dynamic history particularly after the colonial period and it is composed of a melting pot of different cultures. Most of the human settlements are located along the coastal areas and on the western and eastern borders, respectively, along the Maroni and Oyapock rivers. Population growth rate is exacerbating, influenced as well by illegal flows of migrants (Piantoni 2009) coming from Haiti, Brazil, Surinam, Dominican Republic, and other regions and related to illegal gold mining.

Geodiversity Index Assessment

Geodiversity index assessment was performed according to the framework proposed by Pereira et al. (2013), applied and

re-adapted by other authors (Araujo and Pereira 2018; Bétard and Peulvast 2019; Dias et al. 2021). A geodiversity index was calculated as the sum of four partial thematic sub-indices: lithological and unlithified diversity, mineral diversity, hydrodiversity, and geomorphodiversity (Fig. 2). Lithological and unlithified diversity was grouped into one sub-index, while paleodiversity, pedodiversity, and climate diversity were not included since, by our knowledge, no georeferenced and homogenized data are currently available at the regional scale.

Table 1 shows the initial data used for each sub-index, their spatial precision, and the data sources, provided by the on-line platform *GeoGuyane*. Lithological and unlithified diversity was assessed based on the geological map of French Guiana edited in 2001 by the French Geological Survey at the scale of 1:500,000 (BRGM 2001) (Table 1 and Fig. 3a). Mineral diversity sub-index was calculated combining the map of mineral occurrences with the cartography of the secondary gold deposits located in French Guiana (Fig. 3b). The hydrodiversity sub-index was assessed combining three different datasets involving surface and groundwater resources (Table 1 and Fig. 3c). Finally, geomorphodiversity was assessed using the geomorphological map produced by Guitet et al. (2013) according to landform and landscape features (Fig. 3d).

Data were kept at their original spatial resolutions and they were processed through ArcMap 10.8.1 and QGIS Desktop 3.10.13. The Coordinate Reference System used was the RGFG 95 UTM 22 North. After a pre-processing phase to homogenize initial data geometry, a layer of grid-cells of 10×10 km² size was created on the study area (Fig. 2). The geoprocessed data were intersected with the grid in order to obtain, for each cell, multiple polygons related to each sub-index. The centroids of each newly created polygon were extracted and counted on a cell-basis (Fig. 2) according to the classification field of each layer. This avoided the double counting of multiple entities of the same class within a cell. Finally, each sub-index was assessed according to the number of entities in each cell and re-classified based on Jenks natural breaks on a range from 1 (i.e., low diversity) to 4 (i.e., very high diversity).

According to Pereira et al. (2013), hydrodiversity was the only sub-index calculated on expert-based scoring, instead of the number of entities. Grid-cells located at the interface with the coastal areas and containing the *Petit Saut* reservoir, sedimentary underground waters, and great rivers (i.e., Strahler class equal to 8) were automatically scored with the highest value (i.e., 4). Cells containing moderate streams and rivers (i.e., Strahler class equal to 6 and 7) and those containing streams with a Strahler order between 3 and 5 were respectively scored as “3” and “2.” The remaining cells were all scored as “1” because of the presence of low-classed rivers (i.e., Strahler order inferior to 3) and underground water resources of the crystalline basement spread on the whole territory.

The geodiversity index for the study area was the result of the sum of the four sub-index classes (Fig. 2). The index was

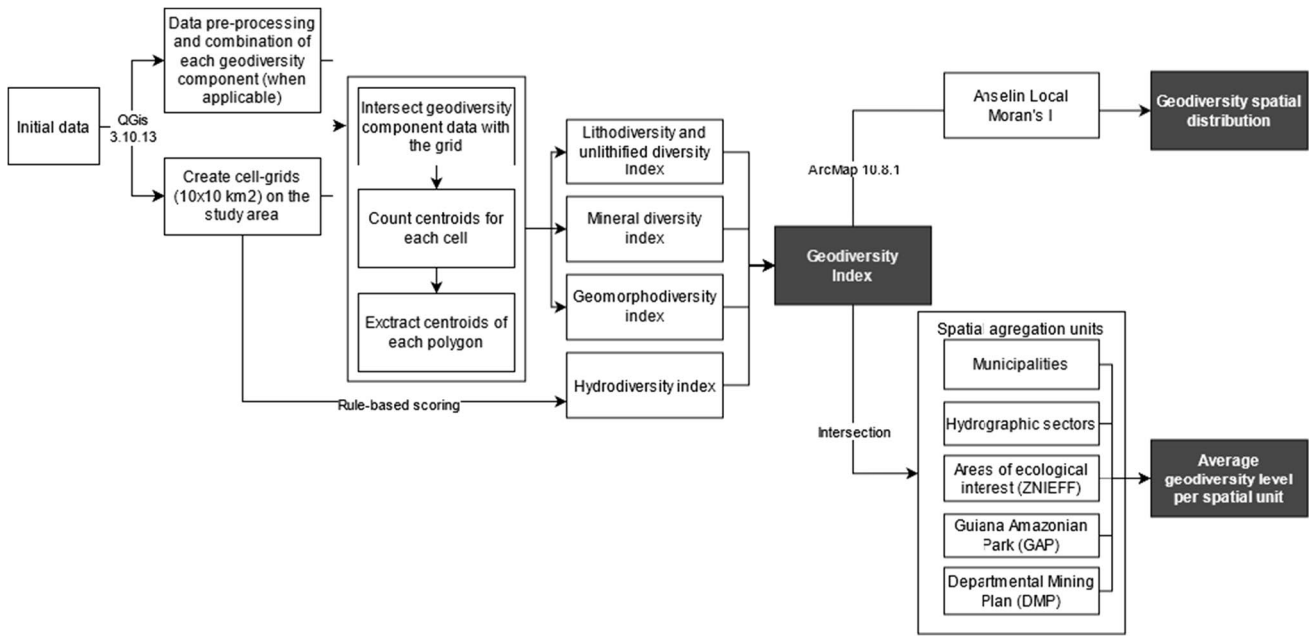


Fig. 2 Methodological flowsheet used to assess the geodiversity index in French Guiana

reclassified according to Jenks natural breaks on a 4-classes range. Geodiversity indices and sub-indices were finally converted into spatially continuous raster values by interpolation of each cell’s centroid using kriging method.

Analysis of Spatial Patterns

The spatial patterns of the geodiversity index were analyzed through local spatial autocorrelation statistics, which focus on the “location of individual points and allow for the decomposition of global or general statistics into the contribution by each individual observation” (Getis 2007). They were used here to detect geodiversity clusters around an individual location within the study area. Local spatial autocorrelation was performed using the *Cluster and Outlier Analysis* module available in ArcMap 10.8.1, which allows to perform Anselin

Local Moran’s I statistic of spatial association. The index is described by the following equation (Eq. 1):

$$I_i = \frac{x_i - \bar{X}}{S_i^2} \sum_{j=1, j \neq i}^n w_{ij} (x_j - \bar{X}) \tag{1}$$

where x_i is an attribute for feature i , \bar{X} is the mean of the corresponding attribute, w_{ij} is the spatial weight between feature i and j , and:

$$S_i^2 = \frac{\sum_{j=1, j \neq i}^n (x_j - \bar{X})^2}{n - 1} \tag{2}$$

with n equating to the total number of features.

The module was applied directly on the same 10×10-km grids of the geodiversity index layer using geodiversity values as input field.

Table 1 Initial spatial data used for the assessment of the four sub-indices with their resolution, their geometric format, and the datasource

Sub-index	Input data	Resolution	Format	Data source (GeoGuyane)
Lithodiversity Unlithified diversity	Geological map of French Guiana	1:500,000	Polygons	BRGM 2001 updated in 2017
Mineral diversity	Mineral resources maps (displaying mineral indexes, deposits, and secondary gold deposits)	1:500,000	Points	BRGM 2006 updated in 2017
Hydrodiversity	Hydrographic network map	1:100,000	Lines	DEAL et al. 2015
	Underground waterbodies map	1:100,000	Polygons	SANDRE and BRGM 2019
	Surface waterbodies map	n/a	Polygons	DEAL et al. 2013
Geomorphodiversity	Geomorphological landscape map	1:100,000	Polygons	ONF et Guitet 2014

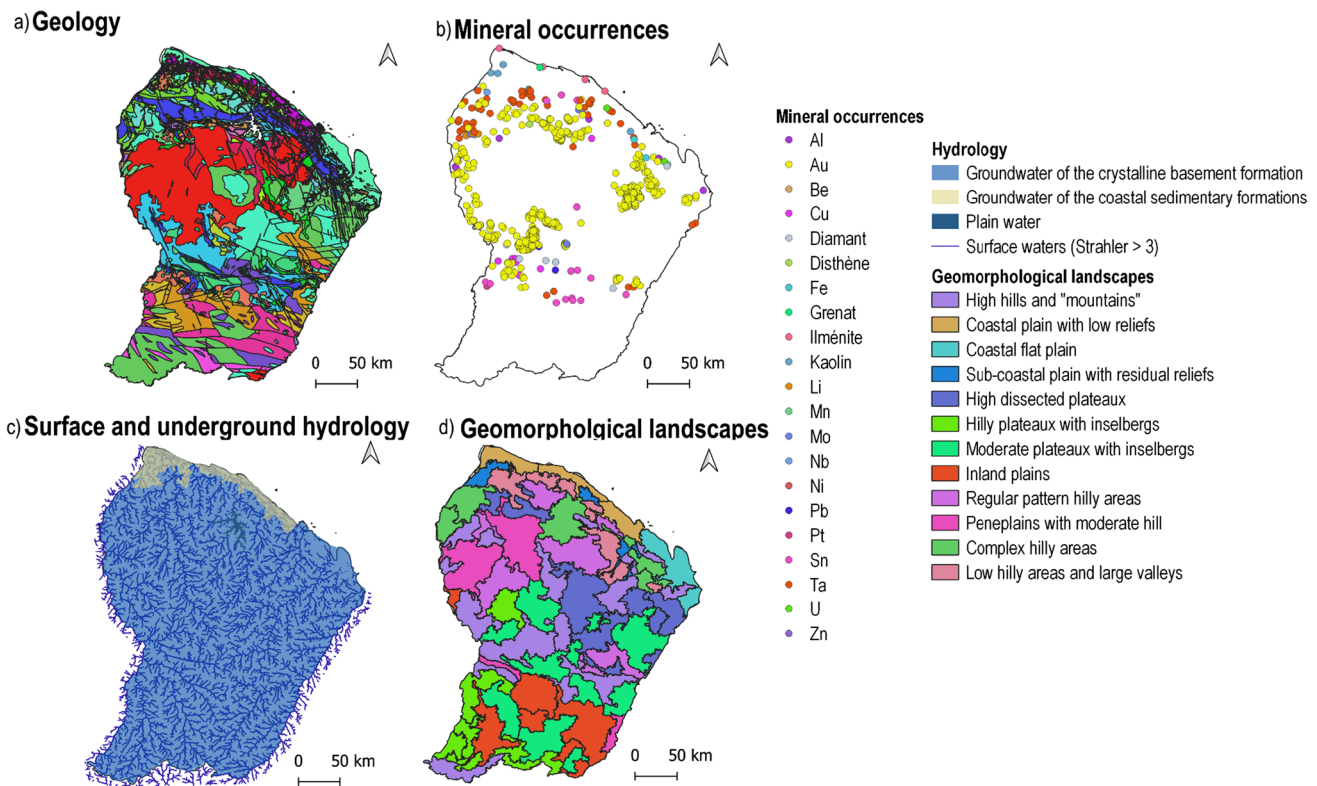


Fig. 3 Initial spatialized data showing the thematic maps used for the assessment of the four geodiversity sub-indices considered in this study, according to lithological and superficial formations (a), min-

eral occurrences and known gold deposits (b), surface streams, plain waterbodies and underground waters (c), and geomorphological features according to forest habitat distribution (d)

Geodiversity Index at Different Spatial Aggregation Units

The geodiversity index was aggregated at five spatial units relevant for land planning and environmental management. The units were chosen according to the administrative divisions at the municipality scale, the hydrographic sectors, the areas of high ecological interests (i.e., ZNIEFF) used for the inventory of fauna and flora, the Guiana Amazonian Park (GAP), and finally the Departmental Mining Plan (DMP) (Table 2). The GAP is divided in two sectors: the “core of the Park,” where a strict environmental regulatory framework is applied to assure strong protection measures, and a “buffer zone” where common law is applied to support local development projects. The DMP is divided in four sectors that state where mining is authorized, authorized with specific limitations, forbidden except for prospecting activities, or totally forbidden. The geodiversity index grid-map was intersected with each of these spatial aggregation units and weighted and averaged for each spatial unit category (e.g., municipality name-field, hydrographic sector name-field, ZNIEFF code, and GAP sector) according to the following equation (Eq. 3):

$$WAGI_u = \sum_{k=1}^n \frac{GI_{u,k} \times A_{u,k}}{A_{u,k}} \quad (3)$$

where $WAGI_u$ is the “weighted averaged geodiversity index” at a given spatial aggregation unit u , and $GI_{u,k}$ and $A_{u,k}$ are respectively the geodiversity index and the surface of the polygon k resulting from the intersection between the grid layer and the layer of the spatial aggregation unit u .

Results

Geodiversity Sub-Indices

Lithodiversity shows higher levels mainly along two areas corresponding to the two greenstone belt branches (Fig. 4a). Low lithodiversity areas are observed on the western side of the territory, where homogeneous granodioritic formations are indicated. Mineral diversity follows the same patterns since most of the prospected mineral occurrences are located along the greenstone belts (Milesi et al. 2003) (Fig. 4b). Null values of hydrodiversity are absent on the whole territory, because of the high density of the hydrological network and the overall presence of streams with

Table 2 Initial spatial data describing the five spatial aggregation unit for the assessment of an average geodiversity index. The classification field describes the layer field used for the aggregation process of the geodiversity index

Spatial aggregation unit	Input data	Scale	Classification field	Data source (GeoGuyane)
Municipalities	French administrative division map	n/a	Municipality name	OpenStreetMap 2017
Hydrographic sectors	Hydrographic sector map	1; 100,000	Hydrographic sector	ONEMA and DEAL 2011
Areas of high-ecological interest for inventory (ZNIEFF)	Merged map of type-1 and type-2 ZNIEFF areas	1; 50,000	ZNIEFF name code	DEAL 2014a, b
Guiana Amazonian Park (GAP)	Guiana Amazonian Park map	1; 500,000	GAP sectors	PAG, WWF 2015
Departmental Mining Plan (DMP)	Departmental Mining Plan map	1; 500,000	DMP type zones	DEAL 2017

low Strahler classes and of groundwater resources related to the formations of the crystalline basement (Fig. 4c). Higher values are located on the coastal areas and along the two main rivers (i.e., Maroni and Oyapock rivers) that separate French Guiana respectively from Suriname (West) and Brazil (East). Finally, high levels of hydrodiversity are found in the grid-cells corresponding to the main rivers inside the territory (Strahler class equal to 7) which highlight the main water catchments. Geomorphodiversity is higher especially in coastal areas and the northern highlands where morphostructural patterns seem to vary the most, particularly between Cayenne and the Eastern coastal plain interacting with the crystalline basement, lateritic duricrusts, the Upper Detrital Unit, and the Demerara and Coswine series of coastal plains (Fig. 4d).

Geodiversity Index and Spatial Patterns

The final geodiversity index shows an overall moderate average value (i.e., 2.1) (Fig. 5a). The index seems to be mainly controlled by lithodiversity and unlithified diversity sub-index, which presents most of the entities in each grid-cell (Fig. 4a). High-geodiversity areas are also influenced by the cells of the coastal zones with the highest hydrodiversity sub-indices. The cluster map (Fig. 5b) obtained through Anselin Local Moran's I provides statistically significant areas of high values (High-High), low values (Low-Low), or areas where high or low values are respectively surrounded by low (High-Low) or high (Low-High) values. High geodiversity clusters correspond to the areas where the two branches of the greenstone belts are located while low geodiversity clusters are located in the South of the territory but also near Kaw estuary (North-East) and along the main homogeneous granodiorite massifs on the Western area, suggesting again the prevalent influence of lithology on the final index.

Average Geodiversity Levels at Different Spatial Aggregation Units

The spatial discretization of the weighted averaged geodiversity index according to different units is presented in Fig. 6. Globally, the figure shows that when aggregating particularly at coarser spatial units, two main sectors are identified: a northern sector with moderate to high geodiversity and a

southern sector with low to moderate geodiversity. At the administrative levels, municipalities located along the central part of the coastal plain such as Sinnamary (i.e., 3.5), Montsinéry-Tonnégrande (i.e., 3.2), and Kourou (i.e., 3), followed by Cayenne (i.e., 2.9), Rémire-Montjoly, Matoury, and, on the western side, Saint-Laurent du Maroni (i.e., 2.7), and other municipalities located within the northern branch of the greenstone belt and the coastal plains form a cluster with the highest geodiversity indices. Moderate to low values are shown by other municipalities such as Saint Georges and Papaïchton (i.e., 1.6), Saul, and Grand Santi (i.e., 1.7) but also Ouanary, Camopi, and Maripasoula (i.e., 1.9) (Fig. 6a).

Generalization is even higher when the index is aggregated at the hydrographic sector level, divided into a northern sector ranging from 2 to 2.8 with the highest peak in the basin of the Kourou and Comté rivers, and one in the south, with moderate to low values ranging from 1.6 in the upstream Oyapock to 1.9 in the Tampok sector. The hydrographic sectors belonging to the Oyapock river basin and the upstream Maroni show overall moderate levels of geodiversity.

The observed geodiversity index averaged for each ZNIEFF area (Fig. 6c) is moderate to very high in the ZNIEFF located along the northern greenstone belt, the coastal plain, and some riverine areas such as the *Alikéné* (i.e., 3.7) and *Gaa Kaba* (i.e., 3.1) mountains, the *Lucifer* massif (i.e., 3.5), or the Approuague river area (i.e., 2.9) and moderately high on the areas located along the greenstone belts. Low levels of geodiversity are mainly found in the south, particularly in the areas of the Upstream Camopi (i.e., 1.5) and the *Tumuc-Humac* mountains (i.e., 1.3).

Moderate to high levels of geodiversity are observed within the buffer zones of the GAP (i.e., 2) while lower levels are located within the core of the park (i.e., 1.7), although with very little differences (Fig. 6d).

Finally, few differences are observed when aggregating at the level of the DMP (Fig. 6e). Areas where mining is authorized, authorized with constraints, or forbidden except for prospecting activities have averaged geodiversity indices respectively of 2.3, 2.4, and 2.5. The areas where mining is totally forbidden present the lowest average geodiversity index (i.e., 1.9).

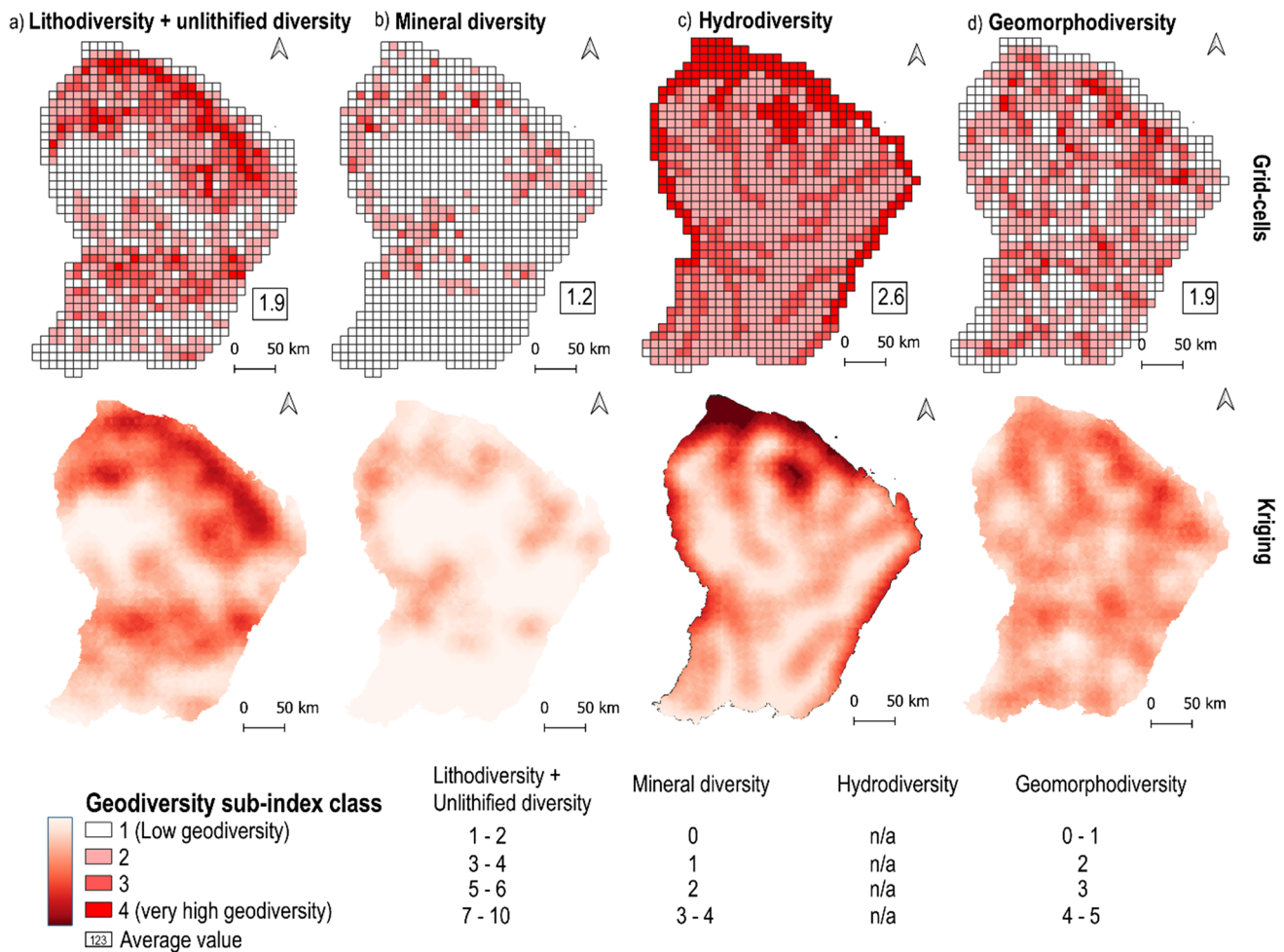


Fig. 4 Grid-based and interpolated (kriging) maps of the four geodiversity sub-indices considered in this study according to the initial data presented in Fig. 3: **a** lithodiversity and unlithified diversity; **b** mineral diversity; **c** hydrodiversity; and **d** geomorphodiversity. The

table below shows, for each sub-index, the number of entities found in each cell. The criterion does not apply to hydrodiversity sub-index which was assessed based on expert-based scoring according to Pereira et al. (2013)

Discussion

The assessment of geodiversity in French Guiana rises multiple questions concerning particularly (i) the dependence of the assessment on the spatial precision and availability of the initial data used and (ii) the representativeness of diversity assessments—in terms of number of different entities in a given location—to globally capture the pivotal role of geodiversity for geoconservation and land planning perspectives.

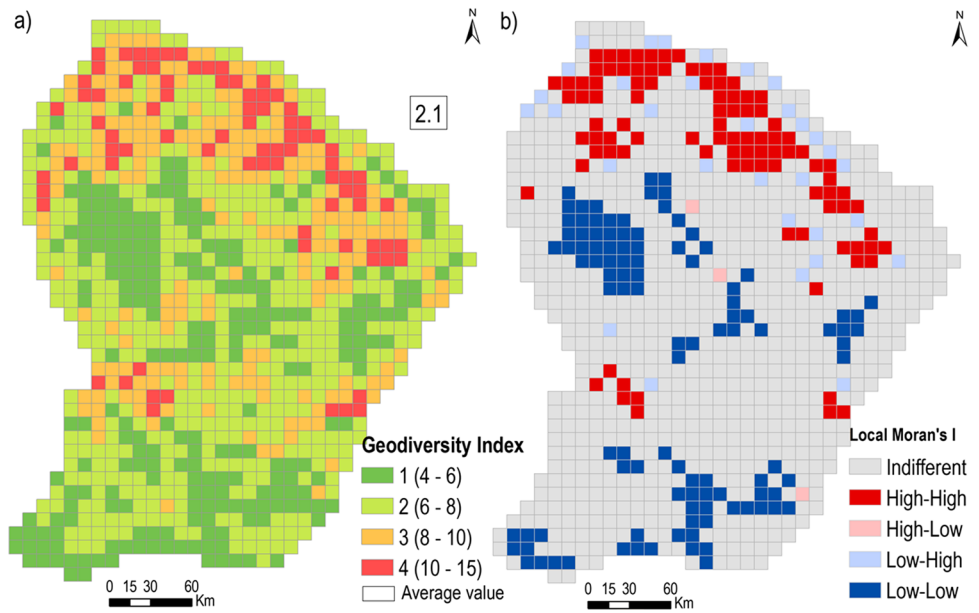
Challenges and Operational Implications of the Assessment of Geodiversity in French Guiana

Geodata Availability in French Guiana

Despite the multiple studies carried over the years by the French Geological Survey (BRGM), French Guiana

lithological map is characterized by multiple imprecisions concerning the different lithological units displayed and their location. Coarser scales might be sufficiently pertinent when an average level of geodiversity is needed at wide spatial extents and more precise spatialized geological data are being developed by the BRGM at the scale of 1:100,000 (Égal et al. 1994, 1995), with the potential to provide helpful information for finer assessments. When comparing the two geological maps (Fig. 7), the increase of spatial precision—with more precise information in terms of geometry and number of lithological units—allows to highlight the underestimation of the lithological sub-index in some areas (e.g., Cayenne) when spatial data are too much coarse. Also, geological maps often do not take into account unlithified diversity (e.g., clay layers, eolian layers) which might alter the diversity of the overlying soils, their properties, and functions.

Fig. 5 Geodiversity index map (a) and geodiversity high and low clusters map according to Anselin Local Moran's index (b). The legend shows the index values which were obtained using Natural Jenks breaks on the sum of the class values of the sub-indices



Mineral diversity sub-index is based on mineral occurrences of gold and other commodities identified on the territory. Indeed, such data were mainly collected for mining prospection purposes. However, on one side, mineral diversity should not be limited to the diversity of mineral

occurrences for mining perspectives only, as mineral commodities of mining and economic interest. A more pertinent proxy to assess such component should encompass mineralogical diversity per se. On the other hand, the presence of multiple occurrences within the greenstone belts—beside

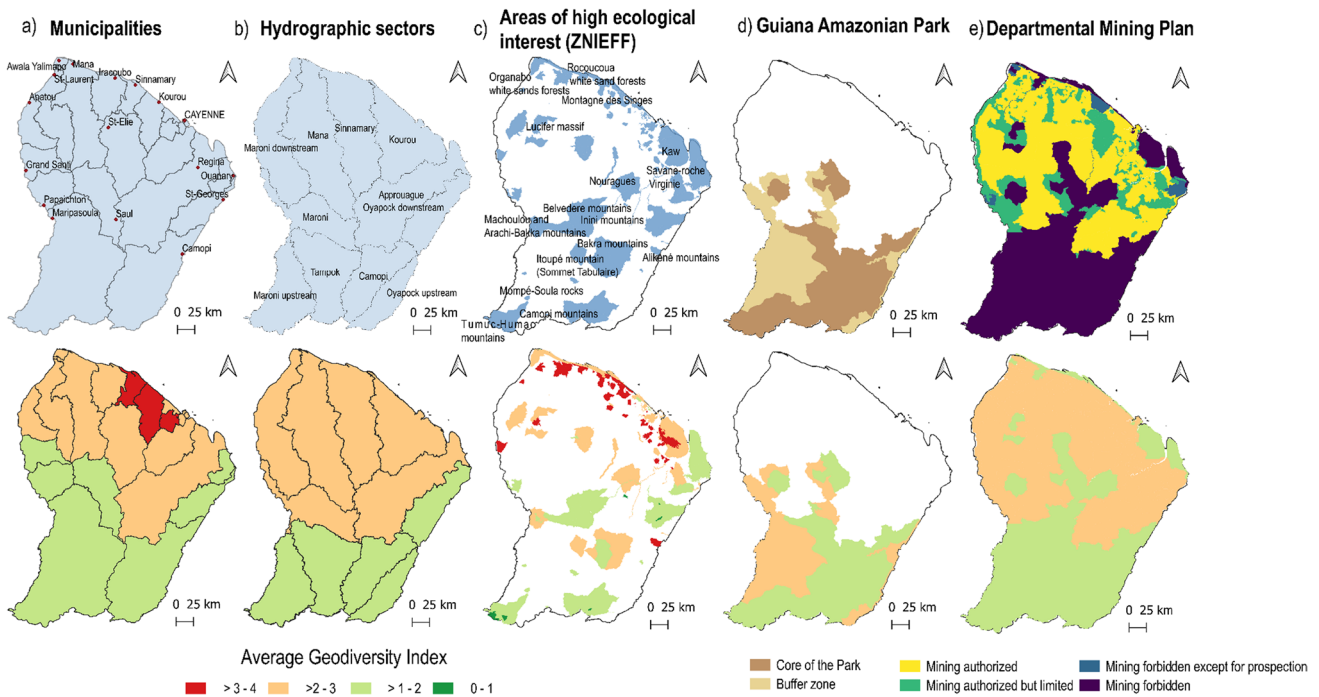


Fig. 6 Aggregation of the geodiversity index at different spatial units: **a** at the administrative level of the municipality; **b** at the hydrographic sector level and **c** at the scale of the areas of high-ecological interest (ZNIEFF); **d** at the scale of the Guiana Amazonian Park

(GAP) (PAG 2018) ; and finally **e** at the scale of the Departmental Mining Plan (DPM). The index was averaged at each unit level and weighted according to polygon surfaces

its geological explanations—might be related to the fact that such areas were the most prospected by the BRGM and mining operators, unlike the areas with granodioritic and granitic units.

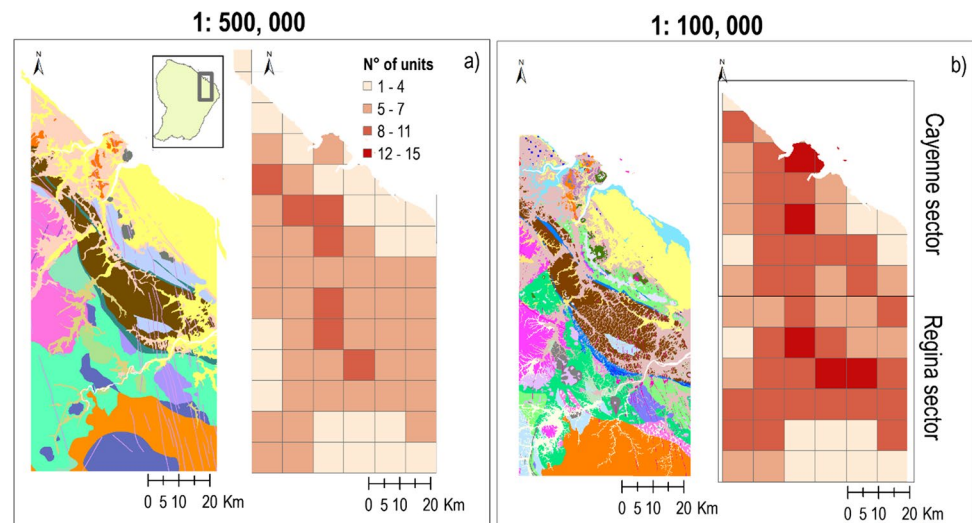
Despite the precision of surface water resources, groundwater diversity in French Guiana is currently classified only in two main units according to the lithological nature of the reservoir. Groundwater bodies are stored within weathered mantles and clay-rich sedimentary units with low permeability but higher storage capacity and within the crystalline basement formations (>95% of the total hydrogeological setting) with high permeability due to fracturing and low storage capacity (Négre and Petelet-Giraud 2010). However, the high lithological variability within the crystalline basement might affect significantly the hydrogeochemical properties of groundwater resources. Groundwater stored within volcanic and metamorphic formations of schists, quartzites, and metavolcanites of the Inferior Paramaca might not show the same geochemical behavior of waters stored within the Superior Paramaca or the plutonic units enriched with orthogneiss, granodiorites, and migmatites (Négre and Petelet-Giraud 2010). The same heterogeneity was observed in groundwater bodies of the sedimentary formations of the coastal plains, where salinization or rainwater quality can significantly affect water geochemistry (Négre and Petelet-Giraud 2010).

Another challenge is the unavailability of specific thematic information covering the whole territory related to soil resources. Soil data are currently available at the 1:50,000 and 1:100,000 scales only for small portions of the territory, based on past studies carried between 1950 and 2000 (Marius and Arthur 1966; Marius 1969; Turenne 1973). Indeed, with the exception of a simplified non-georeferenced soil map provided by Blancaneaux (2001) at the 1:1,000,000 scale, no general spatialized renderings were produced

after 1974 (Leprun et al. 2001). An attempt was realized by the National Forestry Office (ONF) in mapping the main pedotaxa according to forest habitat variability (Guitet et al. 2015) but only typological information was provided and not for all the habitat units. Nevertheless, soils in French Guiana are very heterogeneous with a wide diversity of properties mainly related to lithology and climate regimes. Because of the influence of significant weathering during pedogenesis, they can reach in some cases dozens of meters in depth. Furthermore, weathering contributed to the development of complex physical and geochemical features that, in some soils (e.g., oxisols, ultisols), differentiate the parent materials from the saprolite, alterite, mottled clay layers, and iron-rich crusts (Ferry et al. 2003; Bourbon and Moisan 2013). The diversity of these soils—ranging from poorly developed soils to podzols, hydromorphic soils, and thick oxisols and ultisols (Lévêque 1967; Bravard and Righi 1990; Ferry et al. 2003)—and their properties (e.g., depth, permeability, organic matter content) implies important operational challenges. Better information about French Guiana soils would enhance sustainable land planning in the region in terms, for instance, of water management, agricultural, mine and urban planning, natural hazard control, and forest management (Ferry et al. 2003).

Finally, data about paleodiversity (i.e., the natural range of prehistorical liveforms, fossils, and taphonomic diversity of a given area) are almost non-existent in French Guiana. Araujo and Pereira (2018) suggest two different methods to assess paleodiversity according only to the number of geological units with the presence or potential presence of fossils or considering the total number of fossil species or genera accounted in a cell, based on available data in the scientific literature. Despite globally limiting conditions to fossilization, for instance within the sedimentary units (Antoine et al. 2020) and the absence of paleodiversity assessment

Fig. 7 Comparison of the geological maps of French Guiana at the scale of 1:500,000 (used in this study) with cartographic renderings still under development at finer scales (i.e., 1:100,000) and their impacts on lithodiversity sub-index in the sectors of Cayenne and Regina. Finer spatial data were confidentially provided by French National Survey for geological and mining research (BRGM)



studies, French Guiana paleontological richness was studied by few authors (Watling and Iriarte 2013; Heuret et al. 2021). Watling and Iriarte (2013) study phytoliths of coastal plains and their significant contribution to paleo-ecological and archeological debates in lowland South America. Furthermore, French Guiana witnessed important fossil discoveries over the last decades, the latest dating back to October 2021, when a group of illegal gold miners accidentally discovered the fossil of a 12,000-year-old giant sloth in Maripasoula district (Boulet 2021).

The unavailability of precise spatial data significantly influences the effectiveness of the assessment. Globally speaking, French Guiana geodiversity components remain largely under-documented. The availability of precise information concerning abiotic and interfacial resources is therefore a key challenge to support land planning and to develop sustainable strategies for the region.

Geodiversity of Greenstone Belt Formations

High geodiversity clusters are distributed along two strips that cross French Guiana from west to east in its northern and southern parts (Fig. 5b), which correspond to the location of the Paleoproterozoic greenstone belts, particularly in the northern one (Fig. 8a).

Indeed, according to the methodology used in this study, the geodiversity index proposed by Pereira et al. (2013) focused particularly on georichness, in terms of diversity but not abundance of geotaxa. High geodiversity areas are therefore zones of heterogeneity for class distribution by each grid-cell, which is particularly true in contact and transition areas from one lithological, mineral, hydrological, and geomorphological unit to another one (Dias et al. 2021). Thus, this could be the case of entities related to greenstone belt volcanism, which is often associated to high sheer diversity and to numerous formations with a great variety of geotectonic settings, as suggested by Anhaeusser (2014). Furthermore, it is mainly in these units that gold mineralization occurs, particularly in mesothermal orogenic deposits near sills and shear zones, related to ancient tectonic events (Voicu et al. 2001; Milesi et al. 2003; Théveniaut et al. 2011; Scammacca 2020). For such reasons, the mineral diversity sub-index presents non-null and moderately high values in these areas, contributing to higher levels of geodiversity.

Geologically speaking, the northern branch of the greenstone belt in French Guiana, which presents the widest high-geodiversity cluster (Fig. 8b), is a transition area between the crystalline basement and the two series of sedimentary coastal plain formations. The area is dominantly metasedimentary (e.g., greywackes and pelitic facies of the Armina Formation and conglomerates and sandstones from the Upper Detrital Units) and results from the early recycling of the Archean and Paleoproterozoic crusts (Cassard et al.

2008). The Paleoproterozoic basement also meets here the Quaternary fine sandy-clayey sedimentary formations of marine and fluvio-marine origins of the ancient coastal plain (e.g., Coswine and Coropina series) and the sandy series of the recent coastal plain (e.g., Demerara series) (Delor et al. 2003; Bourbon and Moisan 2013). The southern branch of the greenstone belt has a more marked volcanic and sedimentary variability with acid to basic and ultrabasic volcanic units (Cassard et al. 2008) (Fig. 1). Low geodiversity clusters (Fig. 5b) are mainly located in areas with homogeneous geological settings such as granodioritic and monzogranitic lithologies. However, such areas are also less detailed by geological mapping and mining prospections. This could be due to the accessibility of the area and the significance of the forest cover but also to strategic choices since the greenstone belt areas were the most prospected to identify gold deposits.

The Accordance Between Geodiversity Levels and Land Planning Tools in French Guiana

If the aggregation of an average geodiversity index at different spatial units might introduce a generalization of an already coarse and strongly scale-dependent index, further implications might be inferred concerning the recognition of geodiversity within territorial planning tools. When generalizing at larger spatial units such as in the case of the municipality, hydrographic sector, and DMP levels, a clear distinction between a northern (moderate to high index) and a southern (low to moderate index) regions was observed (Fig. 6a, b, and e).

However, when it comes to implement tools to guide human activities according to environmental management and protection perspectives, three main areas are identifiable. A first group concerns the areas where there is accordance between geodiversity and land planning policies. In such areas, geodiversity presents high values and it is well-recognized by land planning and conservation tools. This is the case for instance of the high geo-ecological areas of *Kaw* mountains, *Lucifer* massif, *Organabo* and *Rocoucoua* white sands forests, *Savane-roche Virginie*, *Alikéné* mountains, or *Montagne des Singes* (Fig. 6c). These areas present indices of very high geodiversity and are recognized areas of significant ecological interest, especially within the formations located between the sedimentary coastal plain, white sand formations, savannas, and inselbergs.

A second group is related to the areas where there is discordance between geodiversity and land planning tools. In a first sub-group, some areas are recognized for environmental management or protection measures but they do not present high geodiversity levels. This is the case, for instance, of the *Coudreau* peak, *Machoulou*, *Bakra*, *Camopi* and *Inini* Mountains, *Belvedere* mountains in *Saul*, *Itoupé*

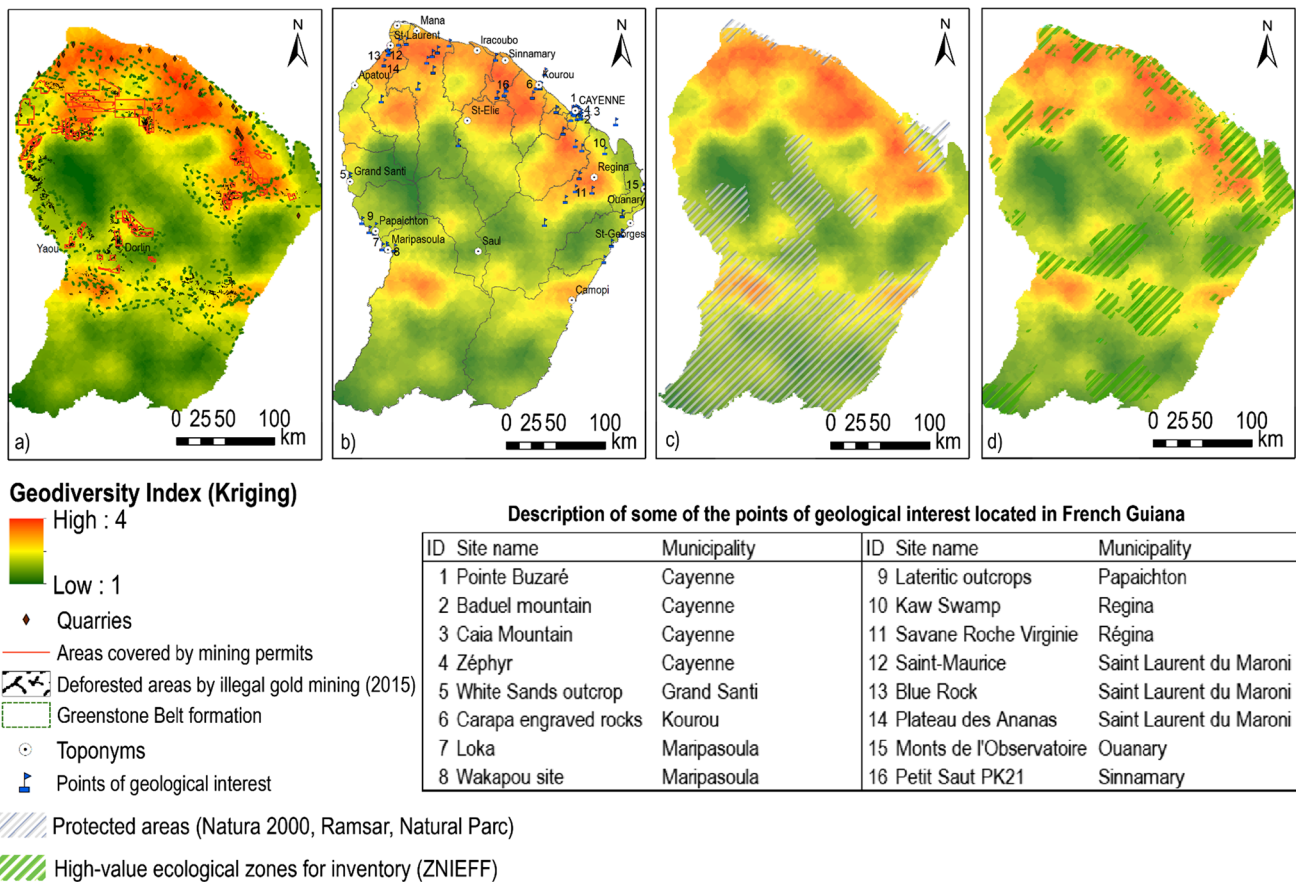


Fig. 8 Interpolated maps of the geodiversity index overlapping socio-ecological features at the regional level in order to compare geodiversity levels with **a** raw material supply in terms of gold-bearing formations and legal (confidential, 2018) and illegal (PAG, WWF 2015) gold mining and quarrying activities (Nontanovanh and Marteau 2010); **b** municipality boundaries and points of geological interest

(only few of them are detailed in the table); **c** protected areas (no distinction made) in the region (DEAL 2002; PAG and WWF 2015); and finally **d** high-value ecological zones (ZNIEFF of type 1 and 2) for the inventory of significant taxa and potential future protection strategies (Deal 2014a, b)

mountain, *Mompé-Soula* rocks, the *Tumuc-Humac* mountains, or the *Nouragues* nature reserve, which is the second largest nature reserve in France, the first one in a populated region, and an important experimental site for national and international research (Ringler et al. 2016). All these areas are recognized as ZNIEFF, suggesting a significant role of abiotic components in biotic processes. Nevertheless, these areas have very low levels of geodiversity. In a second subgroup, other areas presenting strong geodiversity levels are not included within land planning frameworks. For instance, when aggregating at the DPM units, it is shown that the areas with lower geodiversity levels are the ones under a restrictive regime for mining, while, conversely, mining is authorized in areas with higher indices (Fig. 6c). Such assumptions might put in perspective the optimization of regulatory tools such as the Departmental Mining Plan in order to modulate mining access or restrictions taking into account the level of geodiversity. Indeed, this would allow implementing better environmental management or

geoconservation strategies and practices. As example, the integration of stakeholders' involvement through participatory methods could support planning strategies of some high-geodiversity areas. In some of these areas, mineral extraction could be considered as a primary territorial objective, while in others, stakeholders might prioritize geoconservation at the expenses of other activities, including mining. Indeed, if on one hand mineral occurrences—that can also be targeted by mining—positively affect geodiversity levels, they do not represent the only and main driving factor. In any case, it would seem that current mining planning policies in French Guiana do not follow geodiversity patterns, and efforts should be made to fill such gaps. Finally, accordance between geodiversity and spatial planning might be enhanced through the increasing of data precision, particularly in the southern and inner regions of French Guiana to perform more precise assessments and through the integration of the functionality—rather than only the diversity—of abiotic and interfacial resources.

From Geodiversity to Geofunctionality: Is the Assessment of Geodiversity Enough for Sustainable Land Planning?

The Role of French Guiana Geodiversity in Provisioning Processes

The assessment of geodiversity—and of diversity in general—in terms of richness and abundance of entities of different classes in a given area rises a further question. Is the heterogeneity and variation of entities in a given location a sufficiently representative metric to highlight the pivotal role of geodiversity components for the management of a territory?

In this case study, the greenstone belt branches display high geodiversity levels. Such areas present an important functionality in terms of raw material supply since they host multiple deposits of gold and other commodities. As shown by Fig. 8a, gold deposits are often targeted by legal and illegal extraction activities, practiced through a wide range of methods and techniques from artisanal and small to large-scale gold mining (Hammond et al. 2007; Scammacca et al. 2020, 2021). Contrastingly, in other cases, areas known to be significant providers of commodities show low geodiversity values. This is the case, for instance, of the sectors of Dorlin and Yaou, located in the municipality of Maripasoula, which are known to host important gold deposits legally and illegally exploited (Orru, 2001) (Fig. 8a and b). In this case, the discordance between geodiversity level and raw material supply might be caused by the absence of precise data or by particular geological settings not identified where lithological homogeneity does not imply systematically the scarcity of mineral occurrences. Similarly, different areas of the coastal plain with low indices supply construction materials (Fig. 8a) mainly found in surficial and soil formations (e.g., white sands, laterites, weathered granitoids) (Roig and Moisan 2011). Lateritic formations—which cover a great surface of the whole region—have been used for brick construction over centuries, although their functionality varies as a function of the heterogeneity of geological units and laterite textural and mineralogical variability (Sarge et al. 2020).

Geodiversity seems to relate to functionality also in other cases. For instance, Cayenne, Kourou, or Mana municipalities present high geodiversity values (Figs. 6a and 8a)—mainly because of the influence of the hydrodiversity sub-index—and a potentially high functionality in terms of water provisioning. In Cayenne, the Mahury mountain, a crystalline formation of gabbrodiorite, is a natural water-tower hosting a very complex hydrosystem. The site of Couachi is composed of marine and fluvio-marine deposits (Coswine series) and it is the main water provider for the village of Mana with a record water flow of 50 m³ per hour (Parizot et al. 2009). The same geological formations provide 1500

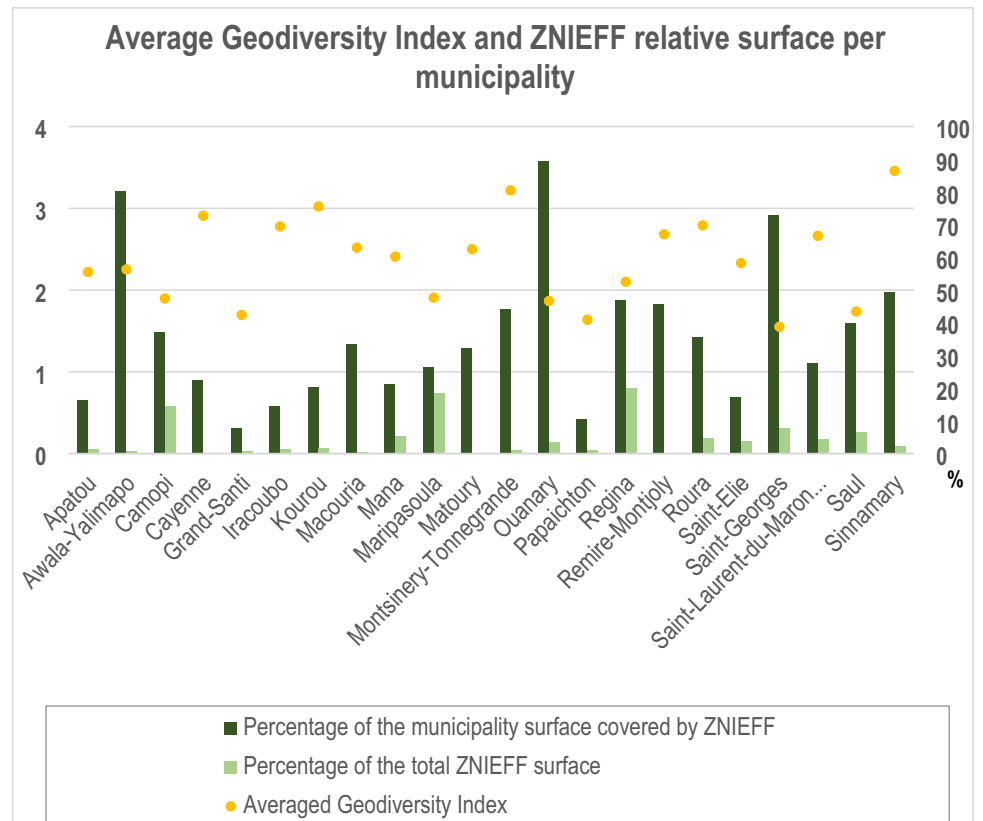
m³ per day in Kourou, which would satisfy the needs of 8000 inhabitants. However, this highlights unequal distribution of the available information that covers more significantly the accessible and populated areas of the coastal plain—where, for instance, the demand of water provisioning is higher—than inner and sparsely populated areas of the territory.

The Role of French Guiana Geodiversity in Regulating Ecological Processes

French Guiana geodiversity might be related as well to biodiversity support, habitat provision, and the regulation of ecological processes. For instance, the importance of geodiversity to the development of specific biotopes and its role in supporting ecological processes could be quantified through data related to natural reserves and protected areas within the territory (Fig. 8c). An operational outcome of such links is the already mentioned DMP, which states where mining can or cannot take place according to ecologically sensitive areas, landscape quality, and populated areas. To illustrate another example, we overlaid the 2014 map ZNIEFF areas—and the interpolated geodiversity index map (Figs. 8d and 9) at the municipality level. Some municipalities are observed to be almost entirely covered by ZNIEFF areas such as Ouanary and Awala-Yalimapo. For instance, Awala-Yalimapo is one of the most important points of geo-ecological interest in French Guiana and the nesting site of three turtle species ranked by the IUCN red list as endangered (Péron et al. 2013). The oviposition phase of these species is controlled by lithology and superficial formations since it requires stable sandy mud-free beaches and their spatial distribution might be significantly influenced by—and influence on—beach morphodynamics (Péron et al. 2013).

Contrasts between geodiversity levels and ZNIEFF areas can be observed in the municipalities of Camopi, Regina, Saint-Georges, or Saul, which shows low levels of geodiversity, hosting at the same time significant areas of high geo-ecological value. The municipality of Regina, with a low averaged geodiversity level (i.e., 1.9), hosts most of the ZNIEFF located in French Guiana (approximately 20%) (Fig. 9). Regina hosts the *Nourague* Nature Reserve, the second largest nature reserve in France and a high-biodiversity area and an important experimental site for national and international research (Ringler et al. 2016). When averaged at finer spatial aggregation units (Fig. 6c), the ZNIEFF area of the *Nourague* reserve shows moderate levels of geodiversity (i.e., 2.16) but, at such scale, geodiversity levels seem to relate to geofunctionality (Fig. 6c). In the same municipality, the *Kaw* swamp is the third largest natural reserve and the first largest wetland in France. Formed during the Quaternary through the fluvio-marine sedimentation of clays and silts and the increase of organic matter content due to anoxic conditions and hydromorphy (Nontanovanh and Roig 2010),

Fig. 9 Weighted average geodiversity indices per municipality compared to the percentage of the municipality surface covered by high-value ecological areas (i.e., ZNIEFF) (dark green). The second column (light green) indicates the percentage of ZNIEFF areas contained in each municipality compared to the total ZNIEFF surface in the whole French Guiana



this swamp is one of the most significant biodiversity clusters in French Guiana hosting rare populations of caimans (i.e., *Melanosuchus niger*, *Caiman crocodilus*, *Paleosuchus palpebrosus*) and important colonies of other reptiles (i.e., *Agama agama*) and of water bird species. Regina hosts as well several mountain landforms, savannas, or the geotouristic sites of the *Balenfois* Mountains or the *Savanne Roche Virginie*, which are granitic inselbergs supporting the development of important biotopes that rely on the geomorphological heterogeneity and the geochemical richness of the underlying lithology (Roig and Moisan 2011).

Another example is Camopi, where, despite a low geodiversity index, almost 40% of the total surface of the municipality is covered by ZNIEFF areas (Fig. 9) related to significant lithological and geomorphological formations including granitic inselbergs and gabbros of the Central Massif of French Guiana (i.e., *Touatou* rock, *Alikéné*, *Itoupé*, and *Bakra* mountains) (Fig. 6c). Similarly, Saul municipality, located along the southern branch of the greenstone belt, presents low geodiversity levels (Figs. 6b and 8b). Nonetheless, this area—currently part of the GAP—is of high biodiversity significance and an important destination for eco-geotourism, due for instance to the presence of granitic inselbergs and the Belvedere mountains (Roig and Moisan 2011) and the site of multiple gold deposits.

Finally, despite the presence of a high-geodiversity cluster (Fig. 8b), Maripasoula presents a global average index of 1.9 when aggregating at larger spatial units such as the municipality. Nevertheless, Maripasoula includes 18% of all ZNIEFF represented in French Guiana in terms of surface (Fig. 9). Among others, the inselbergs of the *Tumuc-Humac* (2.2 Ga), the rock formations of *Koutou*, *Mompé-Soula*, and the mountains of *Arawa*, *Atachi-Bakka*, and *Machoulou* as well as the highest peaks in French Guiana (i.e., *Inini-Camopi*) are located in Maripasoula and they provide particular natural habitats for flora and fauna.

Geoheritage in French Guiana

A specific attention should be given to geodiversity and to the importance of geoheritage as functional feature of geodiversity. Geodiversity and geoconservation are practically inseparable (Serrano and Ruiz-Flaño 2007) and the very notion of geoheritage lies on the scientific, pedagogic, historical, esthetic, and cultural values of geodiversity components, their rarity, or, conversely, their representativeness (Roig and Moisan 2011; Reynard et al. 2016).

French Guiana hosts a significant number of points of geological interest (or geosites) that were inventoried by Nontanovanh and Roig (2010), Roig and Moisan (2011), and Bourbon and Roig (2013). Such geosites are of historical

significance for French Guiana identity but also for geotourism activities and geoconservation practices. For instance, the municipality of Cayenne presents high geodiversity values (Figs. 8b and 9) and multiple points of geological and lithological interest (e.g., *Caïa* hill, *Pointe Buzaré*, *Zéphyr* site, *Baduel* Mountain) (Fig. 8b). The *Pointe Buzaré* is composed of the oldest (2.3 Ga) lithological formations in France and within European Union territories. The *Baduel* Mountain, with other numerous sites in Papaïchton and Saint-Georges municipalities, is among the most studied sites worldwide because of significant lateritic outcrops of more than 60 m thick (Nontanovanh and Roig 2010; Roig and Moisan 2011). Many significant geoheritage sites are located along the northern branch of the greenstone belt, which is also the most accessible, but also along the Maroni and Oyapock rivers and the Quaternary coastal plain (Fig. 8b).

Precambrian (“Blue Rock” site) and sedimentary outcrops (*Saint Maurice* and *Ananas Plateau* sites) are located in Saint-Laurent du Maroni (Nontanovanh and Roig 2010) (Fig. 8b). In this municipality as well as in Grand Santi and in Maripasoula (*Wakapou* site), many outcrops of white sands can be observed (Nontanovanh and Roig 2010; Roig and Moisan 2011). For instance, the sites of *Wakapou* and the *Ananas Plateau* are particularly interesting for the study of podzolization processes (Bourbon and Roig 2013) (Fig. 8b). The *PK21* (Kourou) or *Loka* (Maripasoula) hosts lateritic outcrops > 10 m thick and with significant potential for weathering and natural hazard studies (e.g., landslides, soil erosion) (Nontanovanh and Roig 2010; Bourbon and Roig 2013). The site of *Carapa* in Kourou has also archaeological significance because of the presence of engraved geological formations associated with ancient Native American settlements (Roig and Moisan 2011) (Fig. 8b).

Declining the “Ecosystem Services” Framework to Geodiversity

The discussion between the qualitative relationship between geodiversity and its functions suggests that geodiversity and geofunctionality do not always follow mutual and systematic patterns. Areas with low geodiversity might have high functionality and vice-versa. Therefore, the quantification of geodiversity alone might not take into consideration their contribution to socio-ecological functioning and switching the focus on geofunctionality could have important outcomes for operational purposes. In order to highlight the positive or negative contribution of geodiversity to the functioning of socio-ecological systems, the geoscientific community is increasingly suggesting the declination of the “ecosystem service” (ES) framework (Van Ree et al. 2017; Gray 2018; Fox et al. 2020). Indeed, geodiversity underpins almost all ES across all the service categories (i.e., provisioning, regulating and maintenance, and cultural services) listed by

the existing ES classifications (Fox et al. 2020; Crisp et al. 2021) and authors started referring to “geosystem services” or “geo-ecosystem services” as the services that abiotic and interfacial resources provide to human society (Gray 2005; Gray et al. 2013; Van Ree et al. 2017). Indeed, geodiversity can drive species richness, vegetation heterogeneity and spatial distribution (Bailey et al. 2017; Stavi et al. 2019), and the adaptation of living patterns to droughts and climatic changes (Lawler et al. 2015; Stavi et al. 2018). Several applications focus as well on geodiversity educational potential (Stepišnik et al. 2017; Chrobak et al. 2021) or geoheritage value (Vereb et al. 2020; Ruban et al. 2021). For instance, the relationship previously discussed between French Guiana geodiversity indices and the qualitative appreciation of geofunctionality highlights the role of geodiversity in the supply of both provisioning, regulating, and cultural services.

Integrating the geodiversity concept—whose scope covers a wide range of areas (Schrodt et al. 2019)—within the ES approach might be a key international policy driver for decision-makers (Brilha et al. 2018). Assessing geo-ecosystem services and disservices might lead to more comprehensive sustainable territorial strategies based on geofunctionality rather than geotaxa richness and abundance alone. For instance, soil ES is gaining interest among the scientific community covering geoscientific, ecological, and economic aspects (Dominati et al. 2010; Baveye et al. 2016; Choquet et al. 2021; Mikhailova et al. 2021). Also, quantitative and semi-quantitative approaches for the assessment of the scientific and socio-cultural values of geomorphosites have been proposed by a range of authors (e.g., Reynard et al. 2007, 2016). Globally, multiple authors (Garcia 2019; Tognetto et al. 2021) have already quantified geodiversity-related services. For instance, Butorac and Buzjak (2020) assess geodiversity services of all three service categories: provisioning (freshwater, construction material), regulation (rock cycle, water regulation, biodiversity conservation), and cultural services (esthetic values, recreation). Finally, the methodology proposed by Pereira et al. (2013) used in this study exceptionally assesses hydrodiversity according to parameters that exceed the simple entity richness. When considering the proximity to coastal areas, riverine morphological features, and the Strahler order, the sub-index integrates functional—rather than typological—features of hydrological components, for instance, in terms of water flow, river width for transport, and recreational activities.

Geodiversity per se, as intrinsic value of natural landscapes, is independent from any human uses and perceptions, which are rather incorporated within the concept of geofunctionality or geo-ecosystem services. Therefore, geodiversity alone is not always sufficient for sustainable land planning nor geoconservation perspectives. The functional dimension of geodiversity must be taken into account in order to identify and assess geo-ecosystem services and disservices

according to essential variables and stakeholder perceptions. This should be the next step in the assessment of geodiversity in French Guiana to integrate it into a wider operational framework that switches from the analysis of natural capital of abiotic and interfacial resources towards its contribution to socio-ecological functioning and land planning strategies.

Conclusion

The concept of geodiversity can be an operational tool to highlight the importance of the diversity of abiotic and interfacial resources of a given territory. Geodiversity assessment might serve geoconservation and sustainable land planning purposes. This paper provides the first assessment of a geodiversity index of French Guiana, a territory presenting important abiotic and interfacial resources that can play a pivotal role to support sustainable land planning strategies of the region.

Nevertheless, this study shows that such resources are currently under-documented in French Guiana to assure more precise assessments including all geodiversity components (e.g., paleodiversity, pedodiversity). Some of the spatialized data used are currently too coarse or unavailable to perform precise assessments and this represents a major challenge for sustainable land planning. Future studies should focus on the improvement of existing data and on the collection and harmonization of soil, paleontological, and climatic data.

The results observed for this case study and the qualitative declination of their relevance for territorial management might suggest that the assessment of the variation—in number and types—of geodiversity entities cannot be, alone, always the only useful support to land planning and/or geoconservation practices, particularly when aggregating at larger spatial units. As observed through the example of French Guiana, although qualitatively, geodiversity and geofunctionality do not have a systematic relationship and geodiversity assessment alone might mislead the development of pertinent sustainable planning strategies.

The declination of the “ecosystem services” framework and the quantification of geofunctionality—in terms of geoecosystem services—could fill these gaps providing more precise information concerning (i) the existence of provisioning, regulating, and cultural processes supplied by geodiversity and (ii) the corresponding societal and ecological demand of these services within the socio-ecological system.

Therefore, future studies and methodological frameworks should target the assessment of geodiversity and its functionality within a given area to enhance territorial management. Studying functionality would allow to better apprehend the relationships between anthropogenic driving factors and the capacity of a geo-ecosystem to deliver services to human society and to properly support decision-making. This is particularly true for French Guiana and other developing regions

where forest and environmental management should meet the challenges related to demographic growth, urban sprawl, industrialization, infrastructure development, agricultural intensification, and mining.

Acknowledgements This work was supported by the AgroParisTech (Paris Institute of Technology for Life, Food and Environmental Sciences) and preliminary linked to the project “Pedodiversity and land-planning in French Guiana: development of a harmonized database of French Guiana soils to support land planning” seed-funded by AgroParisTech (APT_032_AO_2022). We thank Olivier Brunaux and Stéphane Guitet of the French Guiana National Forestry Service for proofreading and to provide some of the spatialized data. We are also grateful to Thibaut Brouard of the Technical and Mining Pole of the *Collectivité Territoriale de Guyane* (CTG) to have provided some of the spatialized data related to French Guiana used in this study. We finally thank the two anonymous reviewers for their helpful suggestions and constructive comments which contributed to the improvement of our manuscript.

Declarations

Conflict of Interest The authors declare no competing interests.

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