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1 Geodiversity assessment of French Guiana: challenges and
2 implications for sustainable land planning
3

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19

20 Abstract

21 As operational concept, geodiversity implies a measurement and its application narrowed to a given spatial area,
22 allowing the identification of clusters for prioritization and planning purposes. This study proposes a first
23 geodiversity index assessment for French Guiana, a French Oversea territory located within the Guiana Shield
24 (South America). Almost entirely covered by the Amazon rainforest associated with an exceptional biodiversity,
25 French Guiana appears as an international conservation and land-planning challenge facing multiple issues (e.g.
26 urban, agricultural and industrial growth, forest management, mining planning).

27 Geodiversity assessment is performed through a grid-based approach. A geodiversity index is calculated as the
28 sum of four sub-indices (lithodiversity and unlithified diversity, mineral diversity, hydrodiversity,
29 geomorphodiversity). The index calculation is based on the number of entities within each grid-cell. Spatial
30 correlation is used to identify geodiversity clusters and finally the index is aggregated at different spatial units
31 relevant for land-planning (e.g. municipalities, hydrographic sectors, areas of ecological interest, the Guiana
32 Amazonian Park and the Departmental Mining Plan).

33 The results show that the geodiversity index is mainly controlled by lithodiversity and that high geodiversity
34 clusters are located along the gold-bearing greenstone belts crossing the territory. However, spatialized data
35 concerning geodiversity are still inadequate or unavailable to perform proper operational assessments in French
36 Guiana. Furthermore, based on qualitative examples, we discuss that the assessment of diversity alone might not
37 be always enough for geoconservation nor land-planning perspectives. It is pivotal to account for the
38 geonfunctionality – i.e. the contribution of geodiversity to the functioning of socio-ecological systems – and its
39 interaction with anthropic activities.

40

41 Keywords: geodiversity, quantitative assessment, land planning, ecosystem services, French Guiana.

42 1. Introduction

43 As the abiotic equivalent to biodiversity, “geodiversity” is defined as the “the natural range (diversity) of geological
44 (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological
45 features”, including “their assemblages, structures, systems and contributions to landscapes” (Gray 2013).

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

50 Nieto (2001) defines geodiversity as the number and variability of geological structures and materials within the
51 boundaries of a given area under analysis, highlighting heuristic and operational purposes. This means, on one
52 side, that the geodiversity concept implies the measurement of diversity, in terms, for instance, of richness and
53 abundance. On the other hand, the assessment process must be site-specific, which means that it should be
54 narrowed to a given study area to support context-specific conservation and planning actions (Jie *et al.* 2001; Brocx
55 and Semeniuk 2007).

56 Zwolinski *et al.* (2018) review a wide range of methods to assess geodiversity and distinguish between qualitative
57 methods (e.g. based on expert judgment, descriptive data or on stakeholder’s values) and quantitative methods

58 (e.g. landscape metrics, map algebra, geodiversity indices). Among them, a geodiversity index has been initially
59 proposed by Serrano and Ruiz-Flaño (2007) based on the relationship between a number of physical and
60 geomorphological parameters of a given area. Pereira *et al.* (2013) have proposed a different method, which
61 assesses a geodiversity index as the sum of partial numerical indices calculated over different thematic maps
62 summing the geodiversity entities that occur in grid-cells.

63 Whatever the method used, geodiversity indices have been widely cited in the scientific literature to provide
64 significant spatialized information for land planning purposes (e.g., Benito-Calvo *et al.* 2009; Manosso *et al.* 2015;
65 Araujo and Pereira 2018; Bétard and Peulvast 2019; Dias *et al.* 2021; Vörös *et al.* 2021). Geodiversity can vary
66 through space and time (Manosso *et al.* 2021) and thus, its geovisualization plays a pivotal role for operational
67 applications (Zwolinski *et al.* 2018). Therefore, the spatial associations between geodiversity values within a given
68 area and their spatial patterns can be analyzed to support prioritization actions through the identification of high
69 or low geodiversity clusters (Bétard and Peulvast 2019; Manosso *et al.* 2021). Spatial patterns can be assessed
70 through global or local spatial autocorrelation statistics (Getis 2007) such as Anselin Local Moran's I which has
71 been usually used to assess the spatial relationships between geodiversity and biodiversity. For instance, Manosso
72 *et al.* (2021) assess geodiversity at the river basin scale through both landscape metrics and a geodiversity index
73 and identify geodiversity clusters using Local Moran's Index.

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

81

82 Oversea territories display often-important geo-ecological potentials for sustainable development and conservation
83 strategies, while facing significant land planning and environmental management challenges. Among them, the
84 French Oversea territory of French Guiana is a sparsely populated territory (Le Tourneau 2020) and a
85 highbiodiversity wilderness area (Galochet and Morel 2015) with one of the highest demographic growth rates in
86 France (Millet 2018). Geological resources of French Guiana have been playing a pivotal role in the current and
87 historical territorial dynamics of the region since centuries, mainly because of the presence of gold deposits
88 (Scammacca *et al.* 2021; Jébrak *et al.* 2021). Indeed, georesources of French Guiana are the target of extraction
89 (almost exclusively gold), and prospecting activities, such as for coltan (Gourcerol *et al.* 2019), but also of
90 increasing conservation interest because of their geoheritage, paleontological and archeological potentials and their
91 links with biodiversity habitat support. Furthermore, urban sprawl, agriculture and industrialization are increasing,
92 highlighting the need of sustainable development and land-planning strategies involving multiple human activities
93 and drivers such as forestry, industry, mining, agriculture, tourism and urbanization (Scammacca 2020). For such
94 reasons, French Guiana is a major challenge for socio-ecological management, conservation and sustainable
95 landplanning (Aubertin and Pons 2017). The acknowledgment and characterization of its geodiversity might
96 support policy-making at the territory level in multiple fields (e.g. local water management, mining and urban
97 planning, land-use and development strategies, tourism and conservation).

98 Therefore, this article has the purpose to:

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

105 2. Materials and methods

106 2.1 Socio-geo-ecological settings of the study area

107 Currently under equatorial climate, French Guiana is an Oversea European and French territory of approximately
108 84,000 km² located in South America, between Suriname and the North Region of Brazil (Fig. 1). With more than
109 95% of its surface covered by the Amazonian rainforest and a very dense hydrological network, this region is
110 considered as a high-biodiversity wilderness area (Galochet and Morel 2015). French Guiana geology has been
111 locally documented by the early works of the Overseas Scientific Research Office (Choubert 1949) and the French
112 Geological Survey (BRGM) (Magnien *et al.* 1990) The geological history of the territory is well described by the
113 scientific literature (Vanderhaeghe *et al.* 1998; Delor *et al.* 2003; Milesi *et al.* 2003; Cassard *et al.* 2008; Cordani
114 *et al.* 2009; Théveniaut *et al.* 2012) and it can be framed within the formation of the Guiana Shield, one of the
115 three cratons of the South-American Plate and one of the major Precambrian terrains of Gondwanaland (Delor *et*
116 *al.* 2003).

117 French Guiana geology can be divided within two main geomorphological domains: the uplands of the inner
118 regions occupying 96% of the territory, with moderate relief energy (e.g. hills, multiple granitic inselbergs)
119 reaching a maximum of 850 meters a.s.l., and the coastal plains of the lowlands (4% of the territory). The first
120 domain is composed of outcrops of the oldest crystalline Paleoproterozoic basement mainly composed of
121 magmatic and metamorphic rocks, while the second one is underlined by Quaternary sediments (Fig. 1). The
122 Paleoproterozoic crystalline basement has been formed during the crustal growth of the Transamazonian orogeny
123 (2.25-1.9 Ga) (Vanderhaeghe *et al.* 1998; Delor *et al.* 2003). Five main ensembles can be described:

- 124 - The greenstone belt, which includes two main units: (i) the Paramaca unit, mainly composed of volcanic
125 lithology with greenschist to amphibolite facies metamorphism (i.e., metabasalts, meta-andesites,
126 metadacites and metarhyolites) and (ii) the Armina unit, which is mainly composed of poorly known
127 metavolcanosedimentary rocks such as metapelites and metagreywackes.
- 128 - Three main granitoïdic complexes: the Laussat and Tamoury Complex (2.18-2.16 Ga) is located in the
129 north and south part of French Guiana. The Central Complex (2.15-2.13 Ga) is mainly composed of
130 tonalite-trondhjemite-granodiorite and located in the central part of the territory. The late granitic
131 complex (2.11-2.08 Ga) is located in the eastern part of the territory (e.g. Saint Georges).
- 132 - The Rosebel unit, which crops out in the northern part of French Guiana and is mainly composed of
133 quartzites, metaconglomerate and, to a lesser extent, metapelites.

- 134 - The mafic and ultramafic massif (2.149-2.144 Ga), disseminated in the entire territory and composed of
135 gabbro, gabbro and granodiorite. Sometimes pyroxenolites and peridotites or serpentinites are also
136 observed.
- 137 - Three series of basic dykes, which crosscut all the Paleoproterozoic units. The Apatoes series (0.1980-1.89
138 Ga) mainly crops out in the eastern part of French Guiana. The Tampok (0.808 Ga) and the Comté series
139 (1.8 Ga) are poorly represented in French Guiana. The Tampok dykes crop out in the southwestern part
140 of the territory whereas the Comté series is mainly located in the central part.

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

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

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

156

157 2.2 Geodiversity index assessment

158 Geodiversity index assessment was performed according to the framework proposed by Pereira *et al.* (2013),
159 applied and re-adapted by other authors (Araujo and Pereira, 2018; Bétard and Peulvast, 2019; Dias *et al.* 2021).
160 A Geodiversity Index was calculated as the sum of four partial thematic sub-indices: lithological and unlithified
161 diversity, mineral diversity, hydrodiversity and geomorphodiversity (Fig. 2). Lithological and unlithified diversity
162 were grouped into one sub-index, while paleodiversity, pedodiversity and climate diversity were not included
163 since, by our knowledge, no georeferenced and homogenized data are currently available at the regional scale.

164 Table 1 shows the initial data used for each sub-index, their spatial precision and the data sources, provided by the
165 on-line platform *GeoGuyane*. Lithological and unlithified diversity were assessed based on the geological map of
166 French Guiana edited in 2001 by the French Geological Survey at the scale of 1:500,000 (BRGM, 2017) (Table 1
167 and Fig. 3a). Mineral diversity sub-index was calculated combining the map of mineral occurrences with the
168 cartography of the secondary gold deposits located in French Guiana (Fig. 3b). The hydrodiversity sub-index was
169 assessed combining three different datasets involving surface and groundwater resources (Table 1 and Fig. 3c).

170 Finally, geomorphodiversity was assessed using the geomorphological map produced by Guitet *et al.* (2013)
171 according to landform and landscape features (Fig. 3d).

172 Data were kept at their original spatial resolutions and they were processed through ArcMap 10.8.1 and QGIS
173 Desktop 3.10.13. The Coordinate Reference System used was the RGFG 95 UTM 22 North. After a pre-processing
174 phase to homogenize initial data geometry, a layer of grid-cells of 10x10 km² size was created on the study area
175 (Fig. 2). The geoprocessed data were intersected with the grid in order to obtain, for each cell, multiple polygons
176 related to each sub-index. The centroids of each newly created polygon were extracted and counted on a cell-basis
177 (Fig. 2) according to the classification field of each layer. This avoided the double counting of multiple entities of
178 the same class within a cell. Finally, each sub-index was assessed according to the number of entities in each cell
179 and re-classified based on Jenks natural breaks on a range from 1 (i.e. low diversity) to 4 (i.e. very high diversity).

180 According to Pereira *et al.* (2013), hydrodiversity was the only sub-index calculated on expert-based scoring,
181 instead of the number of entities. Grid-cells located at the interface with the coastal areas, and containing the *Petit*
182 *Saut* reservoir, sedimentary underground waters and great rivers (i.e. Strahler class equal to 8) were automatically
183 scored with the highest value (i.e. 4). Cells containing moderate streams and rivers (i.e. Strahler class equal to 6
184 and 7) and those containing streams with a Strahler order between 3 and 5 were respectively scored as “3” and
185 “2”. The remaining cells were all scored as “1” because of the presence of low-classed rivers (i.e. Strahler order
186 inferior to 3) and underground water resources of the crystalline basement spread on the whole territory.

187 The geodiversity index for the study area was the result of the sum of the four sub-index classes (Fig. 2). The index
188 was reclassified according to Jenks natural breaks on a 4-classes range. Geodiversity indices and sub-indices were
189 finally converted into spatially continuous raster values by interpolation of each cell’s centroid using kriging
190 method.

191

192 2.3 Analysis of spatial patterns

193 The spatial patterns of the geodiversity index were analyzed through local spatial autocorrelation statistics, which
194 focus on the “location of individual points and allow for the decomposition of global or general statistics into the
195 contribution by each individual observation” (Getis 2007). They were used here to detect geodiversity clusters
196 around an individual location within the study area. Local spatial autocorrelation was performed using the *Cluster*
197 *and Outlier Analysis* module available in ArcMap 10.8.1, which allows to perform Anselin Local Moran’s I
198 statistic of spatial association. The index is described by the following equation (Eq. 1):

$$199 \quad I_i = \frac{x_i - \bar{X}}{S_i} \sum_{j=1, j \neq i}^n w_{i,j} (x_j - \bar{X})$$

200 where x_i is an attribute for feature i , \bar{X} is the mean of the corresponding attribute, $w_{i,j}$ is the spatial weight between
201 feature i and j , and:
202

203
$$S_{i2} = \frac{\sum_{j=1, j \neq i}^n (x_j - \bar{X})^2}{n - 1}$$

204 with n equating to the total number of features.

205 The module was applied directly on the same 10x10 km grids of the geodiversity index layer using geodiversity
206 values as input field.

207

208 2.4 Geodiversity index at different spatial aggregation units

209 The geodiversity index was aggregated at five spatial units relevant for land-planning and environmental
210 management. The units were chosen according to the administrative divisions at the municipality scale, the
211 hydrographic sectors, the areas of high ecological interests (i.e. ZNIEFF) used for the inventory of fauna and flora,
212 the Guiana Amazonian Park (GAP) and finally the Departmental Mining Plan (DMP) (Table 2). The GAP is
213 divided in two sectors: the “core of the Park”, where a strict environmental regulatory framework is applied to

209 assure strong protection measures, and a “buffer zone” where common law is applied to support local development
 210 projects. The DMP is divided in four sectors that states where mining is authorized, authorized with specific 211
 limitations, forbidden except for prospecting activities or totally forbidden. The Geodiversity Index grid-map was 212
 intersected with each of these spatial aggregation units and weighted and averaged for each spatial unit category 213 (e.g.
 municipality name-field, hydrographic sector name-field, ZNIEFF code and GAP sector) according to the 214 following
 equation (Eq. 3):

$$215 \quad WAGI_u = \sum_{k=1}^n \frac{GI_{u,k} \times A_{u,k}}{A_{u,k}}$$

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

218 3. Results

219 3.1 Geodiversity sub-indices

220 Lithodiversity shows higher levels mainly along two areas corresponding to the two greenstone belt branches (Fig.
221 4a). Low lithodiversity areas are observed on the western side of the territory, where homogeneous granodioritic
222 formations are indicated. Mineral diversity follows the same patterns since most of the prospected mineral
223 occurrences are located along the greenstone belts (Milesi *et al.* 2003) (Fig. 4b). Null values of hydrodiversity are
224 absent on the whole territory, because of the high density of the hydrological network and the overall presence of
225 streams with low Strahler classes and of groundwater resources related to the formations of the crystalline
226 basement (Fig. 4c). Higher values are located on the coastal areas and along the two main rivers (i.e. Maroni and
227 Oyapock rivers) that separate French Guiana respectively from Suriname (West) and Brazil (East). Finally, high
228 levels of hydrodiversity are found in the grid-cells corresponding to the main rivers inside the territory (Strahler
229 class equal to 7) which highlight the main water catchments. Geomorphodiversity is higher especially in coastal
230 areas and the northern highlands where morphostructural patterns seem to vary the most, particularly between
231 Cayenne and the Eastern coastal plain interacting with the crystalline basement, lateritic duricrusts, the Upper
232 Detrital Unit and the Demerara and Coswine series of coastal plains (Fig. 4d).

233

234 3.2 Geodiversity Index and spatial patterns

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

244

245 3.3 Average geodiversity levels at different spatial aggregation units

246 The spatial discretization of the weighted averaged geodiversity index according to different units is presented in
247 Figure 6. Globally, the figure shows that when aggregating particularly at coarser spatial units, two main sectors
248 are identified: a northern sector with moderate to high geodiversity and a southern sector with low to moderate
249 geodiversity. At the administrative levels, municipalities located along the central part of the coastal plain such as
250 Sinnamary (i.e. 3.5), Montsinéry-Tonnégrande (i.e. 3.2) and Kourou (i.e. 3), followed by Cayenne (i.e. 2.9),
251 Rémire-Montjoly, Matoury and, on the western side, Saint-Laurent du Maroni (i.e. 2.7) and other municipalities
252 located within the northern branch of the greenstone belt and the coastal plains form a cluster with the highest
253 geodiversity indices. Moderate to low values are shown by other municipalities such as Saint Georges and
254 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).

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

260 The observed geodiversity index averaged for each ZNIEFF area (Fig.6c) is moderate to very high in the ZNIEFF
261 located along the northern greenstone belt, the coastal plain and some riverine areas such as the *Alikéné* (i.e. 3.7)
262 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
263 moderately high on the areas located along the greenstone belts. Low levels of geodiversity are mainly found in
264 the south, particularly in the areas of the Upstream Camopi (i.e. 1.5) and the *Tumuc-Humac* mountains (i.e. 1.3).

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

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

4. 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.

4.1 Challenges and operational implications of the assessment of geodiversity in French Guiana

4.1.1 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 (Egal *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 un lithified diversity (e.g. clay layers, aeolian layers) which might alter the diversity of the overlying soils, their properties and functions.

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 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 (Negrel and Petelet-Giraud 2001). 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 behaviour of waters stored within the Superior Paramaca or the plutonic units enriched with orthogneiss, granodiorites and migmatites (Négre and

307 Petelet-Giraud 2001; Négrel and Petelet-Giraud 2010). The same heterogeneity was observed in groundwater
308 bodies of the sedimentary formations of the coastal plains, where salinization or rainwater quality can significantly
309 affect water geochemistry (Négrel and Petelet-Giraud 2001)

310 Another challenge is the unavailability of specific thematic information covering the whole territory related to soil
311 resources. Soil data are currently available at the 1:50,000 and 1:100,000 scales only for small portions of the
312 territory, based on past studies carried between 1950 and 2000 (Marius and Arthur 1966; Marius 1969; Turenne *et*
313 *al.* 1973). Indeed, with the exception of a simplified non-georeferenced soil map provided by Blancaneaux (2001)
314 at the 1:1,000,000 scale, no general spatialized renderings were produced after 1974 (Leprun *et al.* 2001). An
315 attempt was realized by the National Forestry Office (ONF) in mapping the main pedotaxa according to forest
316 habitat variability (Guitet *et al.* 2015) but only typological information was provided and not for all the habitat
317 units. Nevertheless, soils in French Guiana are very heterogeneous with a wide diversity of properties mainly
318 related to lithology and climate regimes. Because of the influence of significant weathering during pedogenesis,
319 they can reach in some cases dozens of meters in depth. Furthermore, weathering contributed to the development
320 of complex physical and geochemical features that, in some soils (e.g. oxisols, ultisols), differentiate the parent
321 materials from the saprolite, alterite, mottled clay layers, and iron-rich crusts (Ferry *et al.* 2003; Bourbon and
322 Moisan 2013). The diversity of these soils – ranging from poorly developed soils to podzols, hydromorphic soils
323 and thick oxisols and ultisols (Léveque *et al.* 1967; Bravard and Righi 1999; Ferry *et al.* 2003) – and their properties
324 (e.g. depth, permeability, organic matter content) implies important operational challenges. Better information
325 about French Guiana soils would enhance sustainable land planning in the region in terms, for instance, of water
326 management, agricultural, mine and urban planning, natural hazard control and forest management (Ferry *et al.*
327 2003).

328 Finally, data about paleodiversity (i.e. the natural range of prehistorical liveforms, fossils and taphonomic diversity
329 of a given area) are almost non-existent in French Guiana. Araujo and Pereira (2018) suggest two different methods
330 to assess paleodiversity according only to the number of geological units with the presence or potential presence
331 of fossils or considering the total number of fossils species or genera accounted in a cell, based on available data
332 in the scientific literature. Despite globally limiting conditions to fossilization, for instance within the sedimentary
333 units (Antoine *et al.* 2020) and the absence of paleodiversity assessment studies, French Guiana paleontological
334 richness was studied by few authors (Watling and Iriarte 2013; Heuret *et al.* 2021). Watling and Iriarte (2013)
335 study phytoliths of coastal plains and their significant contribution to paleo-ecological and archaeological debates
336 in lowland South America. Furthermore, French Guiana witnessed important fossil discoveries over the last
337 decades, the latest dating back to October 2021, when a group of illegal gold miners accidentally discovered the
338 fossil of a 12,000 years old giant sloth in Maripasoula district (Boulet 2021).

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

343

344 4.1.2 Geodiversity of greenstone belt formations

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

348 Indeed, according to the methodology used in this study, the geodiversity index proposed by Pereira *et al.* (2013)
349 focused particularly on georichness, in terms of diversity but not abundance of geotaxa. High geodiversity areas
350 are therefore zones of heterogeneity for class distribution by each grid-cell, which is particularly true in contact
351 and transition areas from one lithological, mineral, hydrological, geomorphological unit to another one (Dias *et al.*
352 2021). Thus, this could be the case of entities related to greenstone belt volcanism, which is often associated to
353 high sheer diversity and to numerous formations with a great variety of geotectonic settings, as suggested by
354 Anhaeusser (2014). Furthermore, it is mainly in these units that gold mineralization occurs, particularly in
355 mesothermal orogenic deposits near sills and shear zones, related to ancient tectonic events (Voicu *et al.* 2001;
356 Milesi *et al.* 2003; Théveniaut *et al.* 2011; Scammacca 2020). For such reasons, the mineral diversity sub-index
357 presents non-null and moderately high values in these areas, contributing to higher levels of geodiversity.

358 Geologically speaking, the northern branch of the greenstone belt in French Guiana, which presents the widest
359 high-geodiversity cluster (Fig. 8b), is a transition area between the crystalline basement and the two series of
360 sedimentary coastal plain formations. The area is dominantly metasedimentary (e.g. greywackes and pelitic facies
361 of the Armina Formation and conglomerates and sandstones from the Upper Detrital Units) and results from the
362 early recycling of the Archean and Paleoproterozoic crusts (Cassard *et al.* 2008). The Paleoproterozoic basement
363 also meets here the Quaternary fine sandy-clayey sedimentary formations of marine and fluvio-marine origins of
364 the ancient coastal plain (e.g. Cosvine and Coropina series) and the sandy series of the recent coastal plain (e.g.
365 Demerara serie) (Delor *et al.* 2003; Bourbon and Moisan, 2013). The southern branch of the greenstone belt has a
366 more marked volcanic and sedimentary variability with acid to basic and ultrabasic volcanic units (Cassard *et al.*
367 2008) (Fig. 1). Low geodiversity clusters (Fig. 5b) are mainly located in areas with homogeneous geological
368 settings such as granodioritic and monzogranitic lithologies. However, such areas are also less detailed by
369 geological mapping and mining prospections. This could be due to the accessibility of the area and the significance
370 of the forest cover but also to strategic choices since the greenstone belt areas were the most prospected to identify
371 gold deposits.

372 4.1.3 The accordance between geodiversity levels and land planning tools in French Guiana

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

378 However, when it comes to implement tools to guide human activities according to environmental management
379 and protection perspectives, three main areas are identifiable. A first group concerns the areas where there is
380 accordance between geodiversity and land planning policies. In such areas, geodiversity presents high values and
381 it is well recognized by land planning and conservation tools. This is the case for instance of the high geoeological

382 areas of *Kaw* mountains, *Lucifer* massif, *Organabo* and *Rocoucoua* white sands forests, *Savane-roche Virginie*,
383 *Alikéné* mountains, or *Montagne des Singes* (Fig. 6c). These areas present indices of very high geodiversity and
384 are recognized areas of significant ecological interest, especially within the formations located between the
385 sedimentary coastal plain, white sand formations, savannas and inselbergs.

386 A second group is related to the areas where there is discordance between geodiversity and land planning tools. In
387 a first sub-group, some areas are recognized for environmental management or protection measures but they do
388 not present high geodiversity levels. This is the case, for instance, of the *Coudreau* peak, *Machoulou*, *Bakra*,
389 *Camopi* and *Inini* Mountains, Belvedere mountains in Saul, *Itoupé* mountain, *Mompé-Soula* rocks, the
390 *TumucHumac* mountains or the *Nouragues* nature reserve, which is the second largest nature reserve in France,
391 the first one in a populated region, and an important experimental site for national and international research
392 (Ringler *et al.* 2014). All these areas are recognized as ZNIEFF, suggesting a significant role of abiotic components
393 in biotic processes. Nevertheless, these areas have very low levels of geodiversity. In a second sub-group, other
394 areas presenting strong geodiversity levels are not included within land planning frameworks. For instance, when
395 aggregating at the DPM units, it is shown that the areas with lower geodiversity levels are the ones under a
396 restrictive regime for mining, while, conversely, mining is authorized in areas with higher indices (Fig. 6c). Such
397 assumptions might put in perspective the optimization of regulatory tools such as the Departmental Mining Plan
398 in order to modulate mining access or restrictions taking into account the level of geodiversity. Indeed, this would
399 allow implementing better environmental management or geoconservation strategies and practices. As example,
400 the integration of stakeholders' involvement through participatory methods could support planning strategies of
401 some high-geodiversity areas. In some of these areas, mineral extraction could be considered as a primary territorial
402 objective, while in others, stakeholders might prioritize geoconservation at the expenses of other activities,
403 including mining. Indeed, if on one hand mineral occurrences – that can also be targeted by mining – positively
404 affect geodiversity levels, they do not represent the only and main driving factor. In any case, it would seem that
405 current mining planning policies in French Guiana do not follow geodiversity patterns, and efforts should be made
406 to fill such gaps. Finally, accordance between geodiversity and spatial planning might be enhanced through the
407 increasing of data precision, particularly in the southern and inner regions of French Guiana to perform more
408 precise assessments and through the integration of the functionality – rather than only the diversity – of abiotic and
409 interfacial resources.

410

411 4.2 From geodiversity to geofunctionality: is the assessment of geodiversity 412 enough for sustainable land-planning?

413

414 4.2.1 The role of French Guiana geodiversity in provisioning processes

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

419 In this case-study, the greenstone belt branches display high geodiversity levels. Such areas present an important
420 functionality in terms of raw material supply since they host multiple deposits of gold and other commodities. As

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

434 Geodiversity seems to relate to functionality also in other cases. For instance, Cayenne, Kourou or Mana
435 municipalities present high geodiversity values (Fig. 6a and 8a) – mainly because of the influence of the
436 hydrodiversity sub-index – and a potentially high functionality in terms of water provisioning. In Cayenne, the
437 Mahury mountain, a crystalline formation of gabbrodiorite, is a natural water-tower hosting a very complex
438 hydrosystem. The site of Couachi is composed of marine and fluvio-marine deposits (Coswine series) and it is the
439 main water provider for the village of Mana with a record water flow of 50 m³ per hour (Parizot *et al.* 2009). The
440 same geological formations provide 1,500 m³ per day in Kourou, which would satisfy the needs of 8,000
441 inhabitants. However, this highlights unequal distribution of the available information that covers more
442 significantly the accessible and populated areas of the coastal plain – where for instance, the demand of water
443 provisioning is higher – than inner and sparsely populated areas of the territory.

444

445 4.2.2 The role of French Guiana geodiversity in regulating ecological processes

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

459 Contrasts between geodiversity levels and ZNIEFF areas can be observed in the municipalities of Camopi, Regina,
460 Saint-Georges or Saul, which show low levels of geodiversity, hosting at the same time significant areas of high
461 geo-ecological value. The municipality of Regina, with a low averaged geodiversity level (i.e. 1.9) hosts most of
462 the ZNIEFF located in French Guiana (approximately 20%) (Fig. 9). Regina hosts the *Nourague* Nature Reserve,
463 the second largest nature reserve in France and a high-biodiversity area and an important experimental site for
464 national and international research (Ringler *et al.* 2014). When averaged at finer spatial aggregation units (Fig. 6c),
465 the ZNIEFF area of the *Nourague* reserve shows moderate levels of geodiversity (i.e. 2.16) but, at such scale,
466 geodiversity levels seem to relate to geofunctionality (Fig. 6c). In the same municipality, the *Kaw* swamp is the
467 third largest natural reserve and the first largest wetland in France. Formed during the Quaternary through the
468 fluvio-marine sedimentation of clays and silts and the increase of organic matter content due to anoxic conditions
469 and hydromorphy (Nontanovanh and Roig 2010), this swamp is one of the most significant biodiversity clusters
470 in French Guiana hosting rare populations of caimans (i.e. *Melanosuchus niger*, *Caiman crocodilus*, *Paleosuchus*
471 *palpebrosus*) and important colonies of other reptiles (i.e. *Agama agama*) and of water bird species. Regina hosts
472 as well several mountain landforms, savannas or the geotouristic sites of the *Balenfois* Mountains or the *Savanne*
473 *Roche Virginie*, which are granitic inselbergs supporting the development of important biotopes that rely on the
474 geomorphological heterogeneity and the geochemical richness of the underlying lithology (Roig and Moisan
475 2011).

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

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

490

491 4.2.3 Geoheritage in French Guiana

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

497 French Guiana hosts a significant number of points of geological interest (or geosites) that were inventoried by
498 Nontanovanh and Roig (2010), Roig and Moisan (2011), Bourbon and Roig (2013). Such geosites are of historical
499 significance for French Guiana identity but also for geo-ecotourism activities and geoconservation practices. For
500 instance, the municipality of Cayenne presents high geodiversity values (Fig. 8b and Fig.9) and multiple points of
501 geological and lithological interest (e.g. *Caia* hill, *Pointe Buzaré*, *Zéphyr* site, *Baduel* Mountain) (Fig. 8b). The
502 *Pointe Buzaré* is composed of the oldest (2.3 Ga) lithological formations in France and within European Union
503 territories. The *Baduel* Mountain, with other numerous sites in Papaïchton and Saint-Georges municipalities, are
504 among the most studied sites worldwide because of significant lateritic outcrops of more than 60 meters thick
505 (Nontanovanh and Roig 2010; Roig and Moisan 2011). Many significant geoheritage sites are located along the
506 northern branch of the greenstone belt, which is also the most accessible, but also along the Maroni and Oyapock
507 rivers and the Quaternary coastal plain (Fig. 8b).

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

517

518 4.2.4 Declining the “ecosystem services” framework to geodiversity

519 The discussion between the qualitative relationship between geodiversity and its functions suggests that
520 geodiversity and geofunctionality do not always follow mutual and systematic patterns. Areas with low
521 geodiversity might have high functionality and vice-versa. Therefore, the quantification of geodiversity alone
522 might not take into consideration their contribution to socio-ecological functioning and switching the focus on
523 geofunctionality could have important outcomes for operational purposes. In order to highlight the positive or
524 negative contribution of geodiversity to the functioning of socio-ecological systems, the geoscientific community
525 is increasingly suggesting the declination of the “ecosystem service” (ES) framework (Van Ree *et al.* 2017; Gray
526 2018; Fox *et al.* 2020). Indeed, geodiversity underpins almost all ES across all the service categories (i.e.
527 provisioning, regulating and maintenance, and cultural services) listed by the existing ES classifications (Crisp *et al.*
528 2020; Fox *et al.* 2020) and authors started referring to “geosystem services” or “geo-ecosystem services” as the
529 services that abiotic and interfacial resources provide to human society (Gray 2005; Gray *et al.* 2013; Van Ree *et al.*
530 2017). Indeed, geodiversity can drive species richness, vegetation heterogeneity and spatial distribution (Bailey
531 *et al.* 2017; Stavi *et al.* 2019) and the adaptation of living patterns to droughts and climatic changes (Lawler *et al.*
532 2015; Stavi *et al.* 2018). Several applications focus as well on geodiversity educational potential (Stepisnik *et al.*
533 2017; Chrobak *et al.* 2019) or geoheritage value (Vereb *et al.* 2020; Ruban *et al.* 2021). For instance, the
534 relationship previously discussed between French Guiana geodiversity indices and the qualitative appreciation of

535 geofunctionality highlights the role of geodiversity in the supply of both provisioning, regulating and cultural
536 services.

537 Integrating the geodiversity concept – whose scope covers a wide range of areas (Schrodt *et al.* 2019) – within the
538 ES approach, might be a key international policy driver for decision makers (Brilha *et al.* 2018). Assessing
539 geocosystem services and disservices might lead to more comprehensive sustainable territorial strategies based
540 on geofunctionality rather than geotaxa richness and abundance alone. For instance, soil ES are gaining interest
541 among the scientific community covering geoscientific, ecological and economic aspects (Dominati *et al.* 2010;
542 Baveye *et al.* 2016; Choquet *et al.* 2021; Mikhailova *et al.* 2021). Also, quantitative and semi-quantitative
543 approaches for the assessment of the scientific and socio-cultural values of geomorphosites have been proposed
544 by a range of authors (e.g., Reynard *et al.* 2007, 2016). Globally, multiple authors (Alahuntaa *et al.* 2018; Garcia
545 2019; Tognetto *et al.* 2021) have already quantified geodiversity-related services. For instance, Butorac and Buzjak
546 (2020) assess geodiversity services of all three service categories: provisioning (freshwater, construction material),
547 regulation (rock cycle, water regulation, biodiversity conservation) and cultural services (aesthetic values,
548 recreation). Finally, the methodology proposed by Pereira *et al.* (2013) used in this study, exceptionally assesses
549 hydrodiversity according to parameters that exceed the simple entity richness. When considering the proximity to
550 coastal areas, riverine morphological features and the Strahler order, the sub-index integrates functional – rather
551 than typological – features of hydrological components, for instance, in terms of water flow, river width for
552 transport and recreational activities.

553 Geodiversity *per se*, as intrinsic value of natural landscapes, is independent from any human uses and perceptions,
554 which are rather incorporated within the concept of geofunctionality or geo-ecosystem services. Therefore,
555 geodiversity alone is not always sufficient for sustainable land planning nor geoconservation perspectives. The
556 functional dimension of geodiversity must be taken into account in order to identify and assess geo-ecosystem
557 services and disservices according to essential variables and stakeholder perceptions. This should be the next step
558 in the assessment of geodiversity in French Guiana to integrate it into a wider operational framework that switches
559 from the analysis of natural capital of abiotic and interfacial resources towards its contribution to socio-ecological
560 functioning and land planning strategies.

561

562 Conclusion

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

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

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

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

583 Therefore, future studies and methodological frameworks should target the assessment of geodiversity and its
584 functionality within a given area to enhance territorial management. Studying functionality would allow to better
585 apprehend the relationships between anthropogenic driving factors and the capacity of a geo-ecosystem to deliver
586 services to human society and to properly support decision-making. This is particularly true for French Guiana and
587 other developing regions where forest and environmental management should meet the challenges related to
588 demographic growth, urban sprawl, industrialization, infrastructure development, agricultural intensification and
589 mining.

590

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600 Statements and Declarations

601 Conflict of Interest

602 The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the
603 manuscript and there is no financial interest to report. We certify that the submission is original work and is not
604 under review at any other publication.

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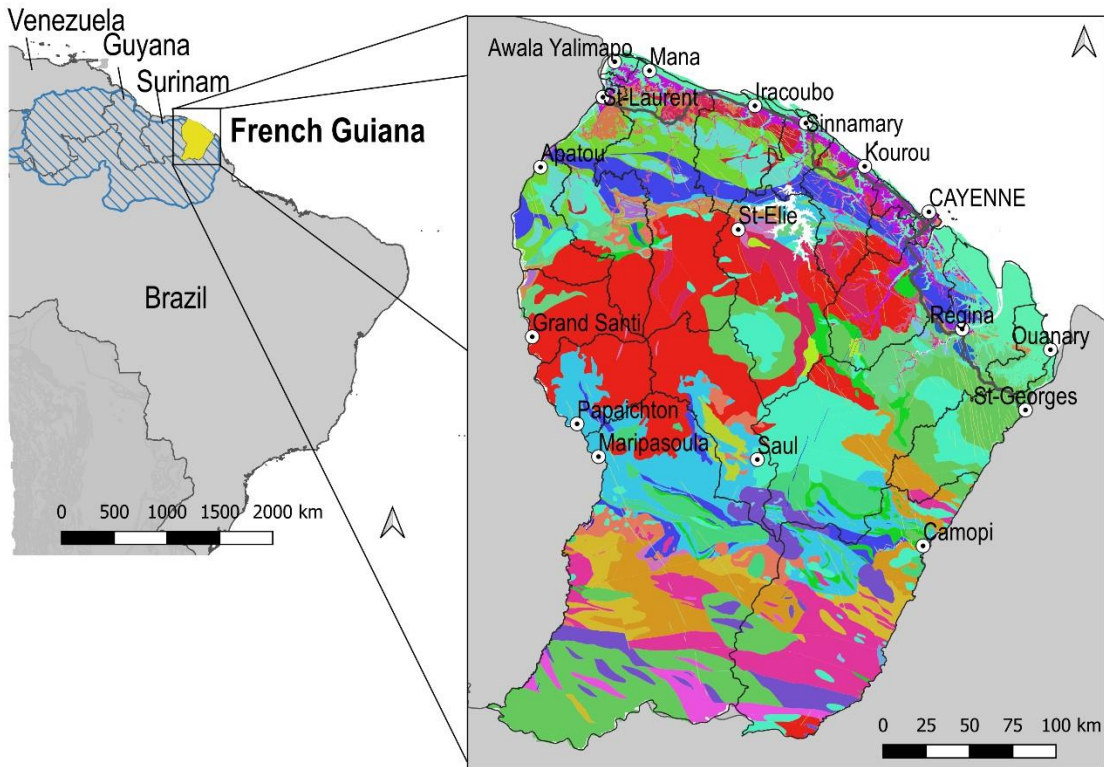
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878 Figures

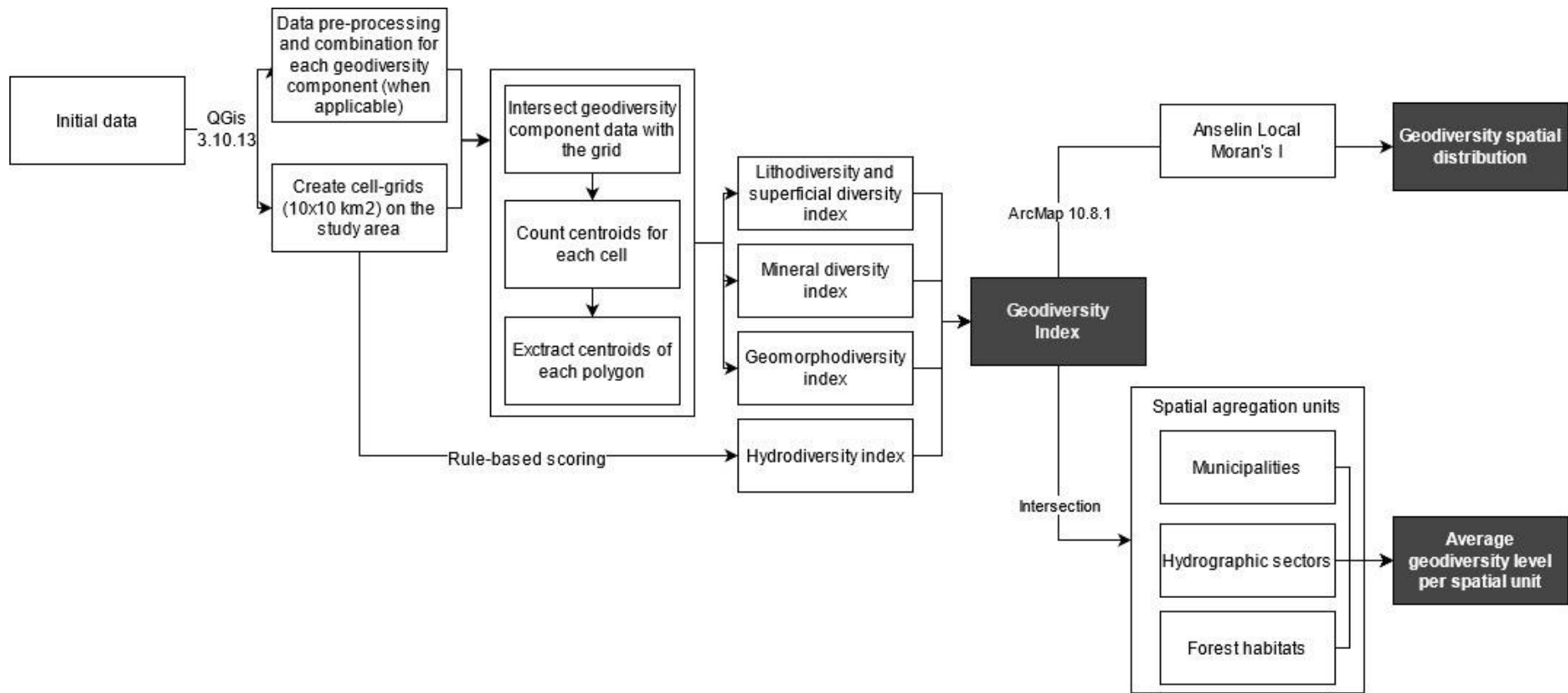
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- ⊙ Toponyms
 - Primary roads
 - Municipalities
 - ▨ Guiana Shield
- Geological map (Brgm, 2001)**
- Alluvial and superficial formations
 - Basic and ultrabasic (chamoenderbites, enderbites)
 - Basic and ultrabasic (cortlandtite, wehrite, pyroxenite, gabbro-norite)
 - Graniodioritic diatexites
 - Microgabbros dykes
 - Microgabbros dykes with olivine-clinopyroxen
 - Basaltic sills and tholeiitic microgabbros
 - Gabbronorites, gabbros
 - Gabbros (île de Cayenne)
 - Granits, pegmatites (Nb-Ta)
 - Granodiorites
 - Granodiorites (monzogranites)
 - Granodiorites (porphyric monzogranites)
 - Grauwacques
 - Pelitic sandstones and quartzites
 - Sandstones and quartzites (conglomerates)
 - Recent sandstones and quartzites
 - Peraluminous leucogranites
 - Monzogranites
 - Metaluminous monzogranites and pegmatites
 - Lutites
 - Rhyolites (Monts Belvedere)
 - Coswine serie
 - Demerara serie
 - White Sands serie
 - Ultramafic serie (komatites)
 - Tonalitic and granodioritic plutons
 - Syenites
 - Downstream Maroni terrasses
 - Tonalites, granodiorites
 - Tonalites, microdiorites
 - Trondhjemites (île de Cayenne)
 - Trondhjemites, tonalites, granodiorites
 - Basic volcanism (amphibolites)
 - Calco-alcalin, acid, intermediary volcanism
 - Indifferenciated volcanism
 - Volcanites, volcano-sediments

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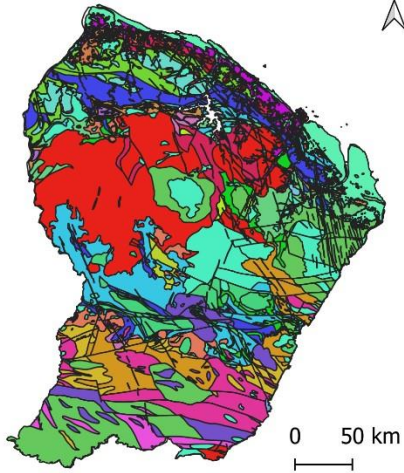
881 *Figure 1 Localization and geological map of the study area with the administrative boundaries and primary roads.*



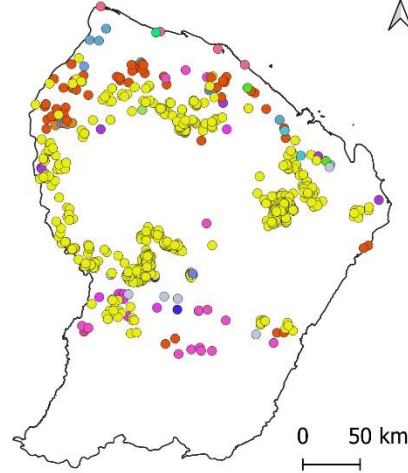
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889 *Figure 2 Methodological flowsheet used to assess the Geodiversity Index according to the methodology proposed by Pereira et al., (2013).*

a) **Geology**



b) **Mineral occurrences**



Mineral occurrences

- Al
- Au
- Be
- Cu
- Diamant
- Disthène
- Fe
- Grenat
- Ilménite
- Kaolin
- Li
- Mn
- Mo
- Nb
- Ni
- Pb
- Pt
- Sn
- Ta
- U
- Zn

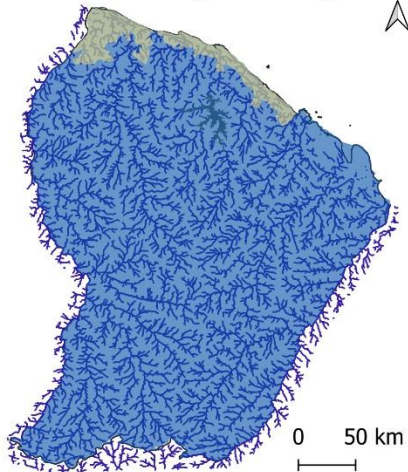
Hydrology

- Groundwater of the crystalline basement formation
- Groundwater of the coastal sedimentary formations
- Plain water
- Surface waters (Strahler > 3)

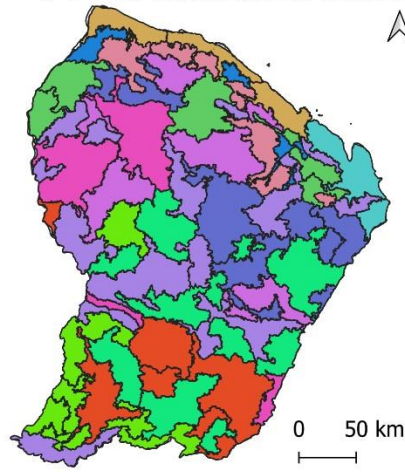
Geomorphological landscapes

- High hills and "mountains"
- Coastal plain with low reliefs
- Coastal flat plain
- Sub-coastal plain with residual reliefs
- High dissected plateaux
- Hilly plateaux with inselbergs
- Moderate plateaux with inselbergs
- Inland plains
- Regular pattern hilly areas
- Peneplains with moderate hill
- Complex hilly areas
- Low hilly areas and large valleys

c) **Surface and underground hydrology**



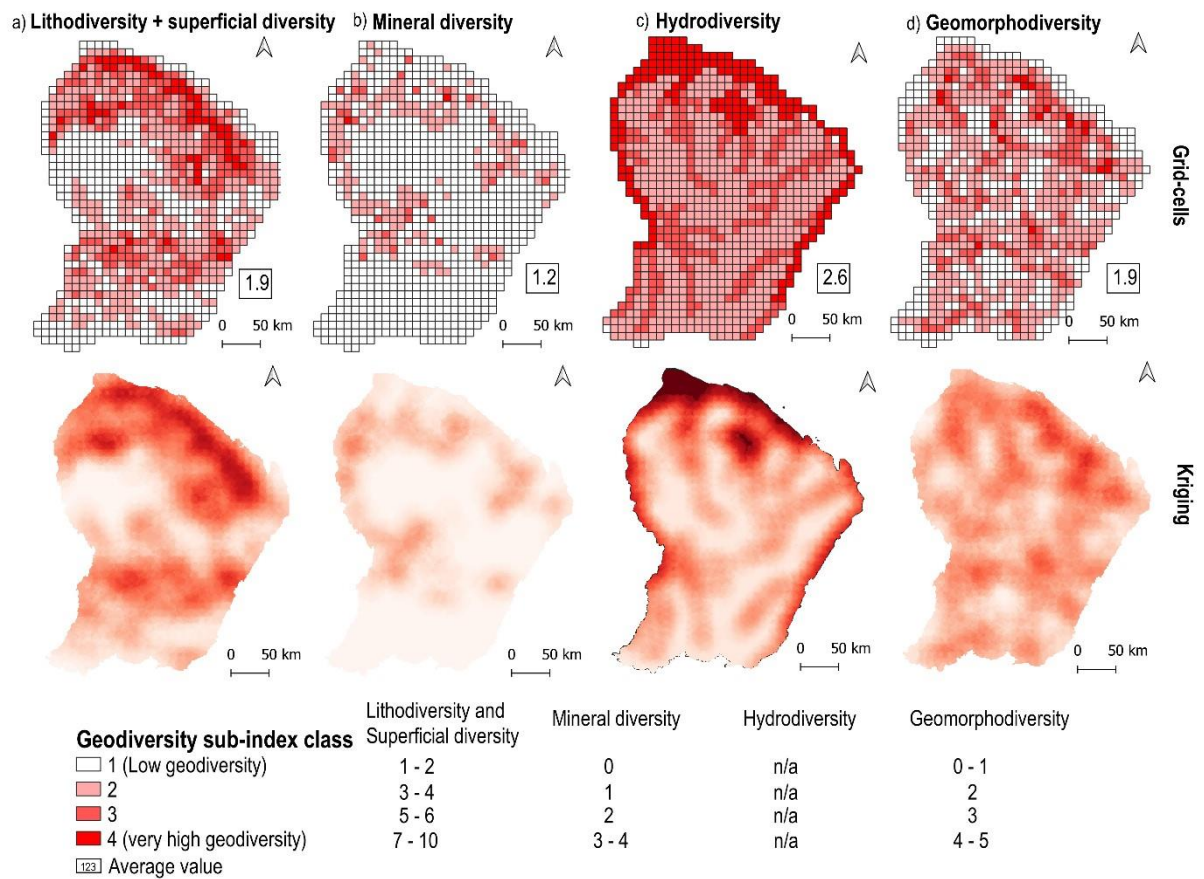
d) **Geomorphological landscapes**



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891 Figure 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

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



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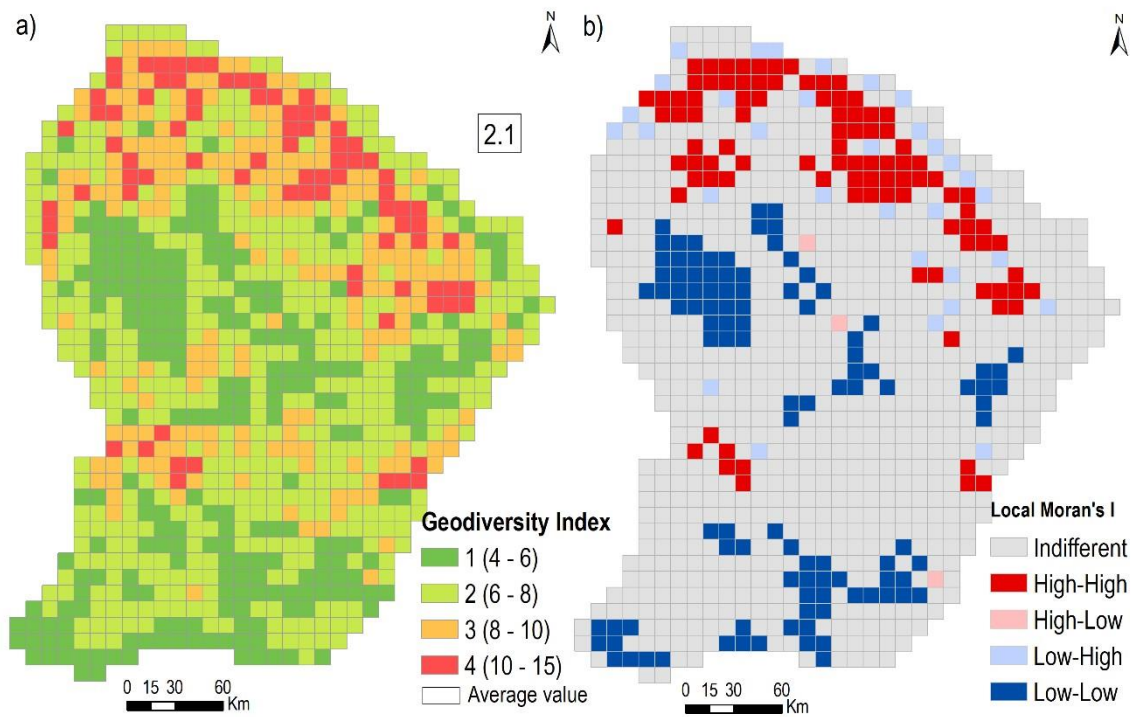
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Figure 4 Grid based and interpolated (kriging) maps of the four geodiversity sub-indices considered in this study according to the initial data presented in Fig.3: a) lithodiversity and superficial diversity; b) mineral diversity; c) hydrodiversity and d) geomorphodiversity. The table below show the abundance, for each sub-index, of the 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).

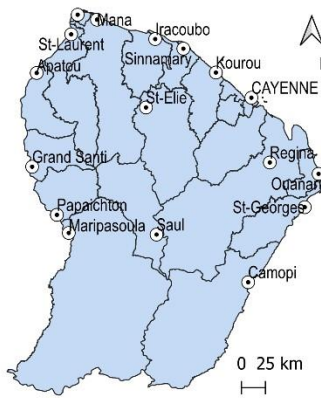


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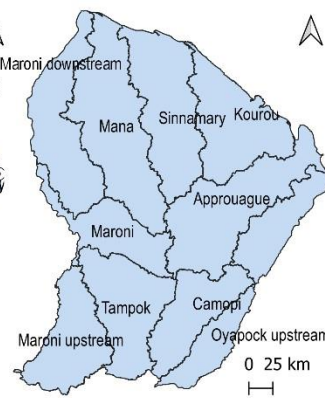
900 *Figure 5 Geodiversity Index map (a) and Geodiversity High and Low clusters map according to Anselin Local Moran's Index (b).*

901 *The legend show the index values which were obtained using Natural Jenks breaks on the sum of the class values of the sub902 indices.*

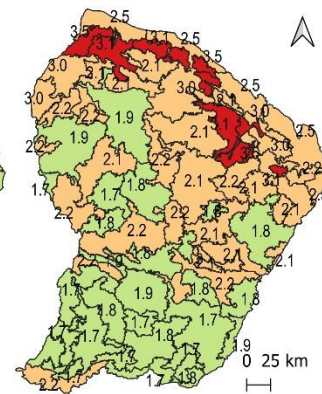
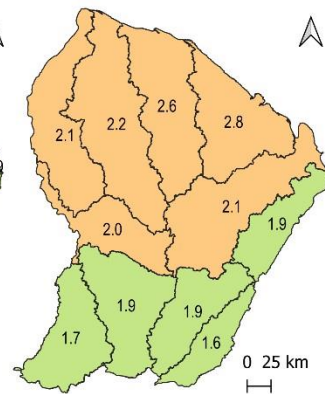
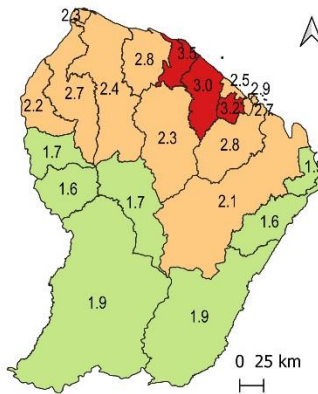
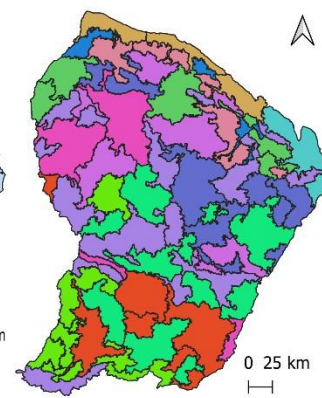
a) Municipalities



b) Hydrographic sectors



c) Forest habitats



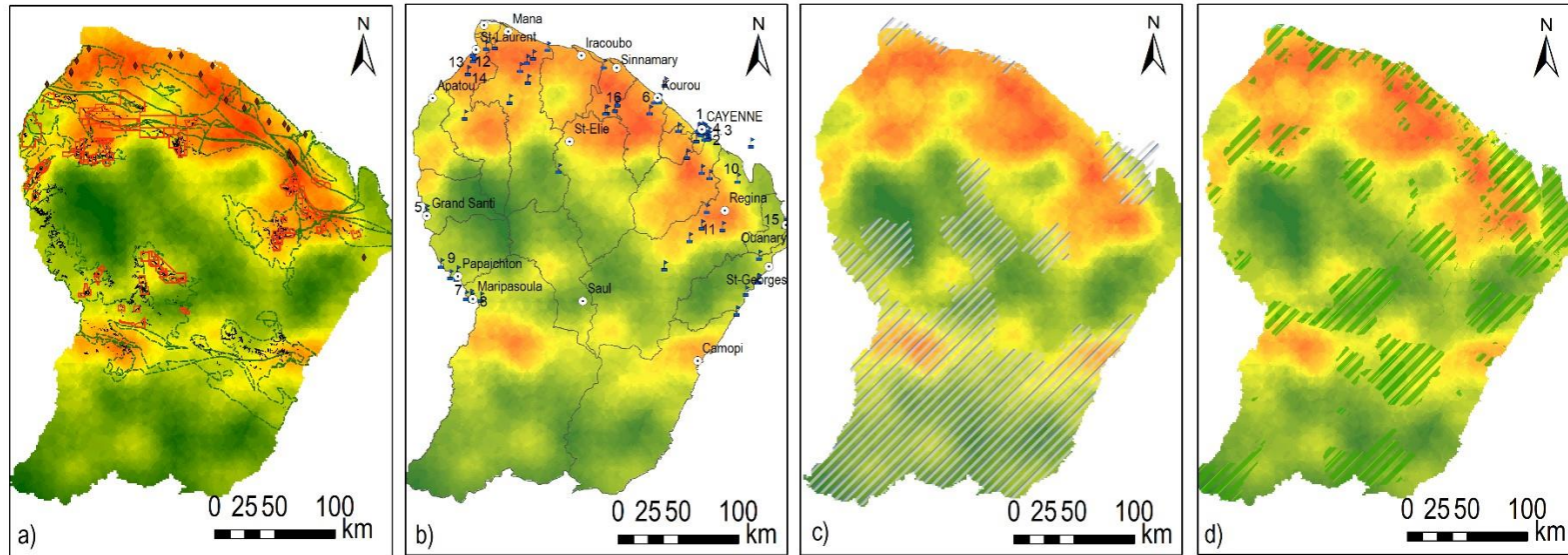
Geodiversity Index (Weighted average)

- 0 - 1
- > 1 - 2
- > 2 - 3
- > 3 - 4

Type of forest habitats (Guitet et al., 2013; ONF, 2015)

- Mountain high forests (Mimosoideae, Burseraceae, Vochysiaceae)
- Littoral and coastal plain forests
- Littoral and coastal plain forests (no relief)
- Sub-coastal forests of the ancient coastal plain on detrital sand units
- High plateaux forests (Mimosoideae)
- High plateaux forests (Angelique, Sali)
- Low plateaux forests (Moni, Giupi, palm trees)
- High forests with multi-concave landforms (Burseraceae, Mimosoideae, Myristicaceae)
- High plateaux forests with high hills (Faboidae)
- Complex plateaux forests with wide palm trees (Arecaceae)
- Complex plateau forests and Northern trench hills (Maho, Amaranth)
- Fluvial valleys forests of the North (Wapa, Lecythidaceae)

904 *Figure 6 Aggregation of the Geodiversity Index at different spatial units: a) at the administrative level of the municipality; b) 905*
at the hydrographic sector level and c) at the scale of forest habitat units. The Index was averaged at each unit level and 906 weighted
according to polygon surfaces.



Geodiversity Index (Kriging)

High : 4



Low : 1

◆ Quarries

— Areas covered by mining permits

🌳 Deforested areas by illegal gold mining (2015)

🟩 Greenstone Belt formation

⊙ Toponyms

🚩 Points of geological interest

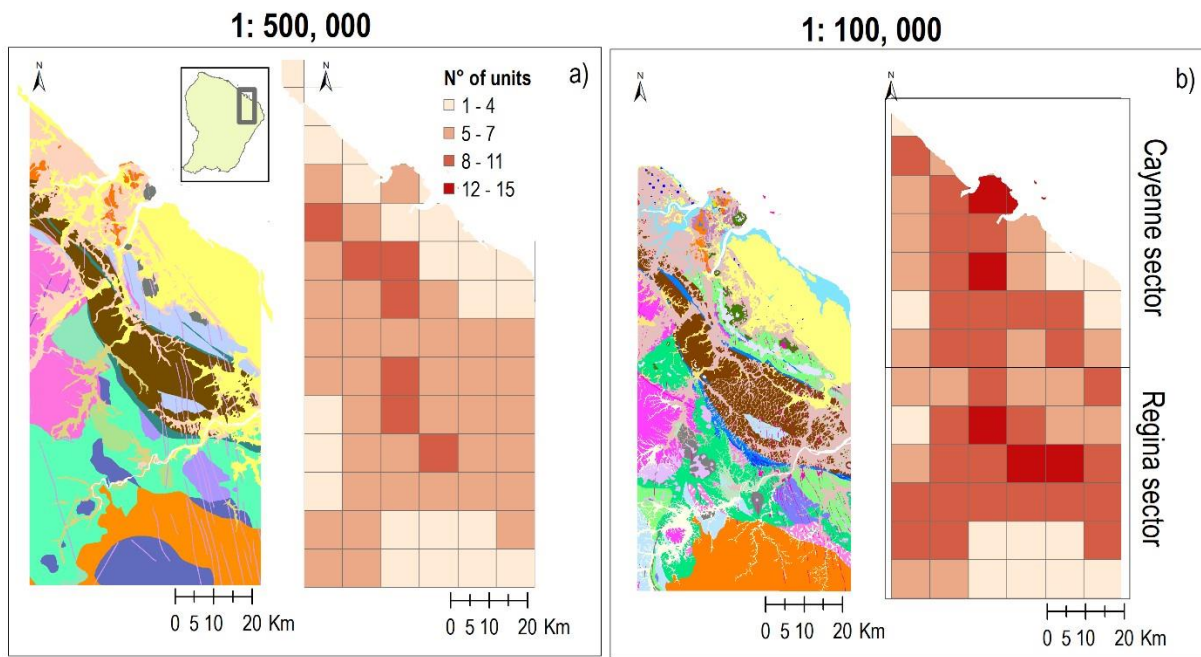
▨ Protected areas (Natura 2000, Ramsar, Natural Parc)

▨ High-value ecological zones (ZNIEFF)

Description of some of the points of geological interest located in French Guiana

ID	Site name	Municipality	ID	Site name	Municipality
1	Pointe Buzaré	Cayenne	9	Lateritic outcrops	Papaïchton
2	Baduel mountain	Cayenne	10	Kaw Swamp	Régina
3	Caïa Mountain	Cayenne	11	Savane Roche Virginie	Régina
4	Zéphyr	Cayenne	12	Saint-Maurice	Saint Laurent du Maroni
5	White Sands outcrop	Grand Santi	13	Blue Rock	Saint Laurent du Maroni
6	Carapa engraved rocks	Kourou	14	Plateau des Ananas	Saint Laurent du Maroni
7	Loka	Maripasoula	15	Monts de l'Observatoire	Ouanary
8	Wakapou site	Maripasoula	16	Petit Saut PK21	Sinnamary

908 *Figure 7 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*
909 *gold-bearing formations and legal and illegal gold mining and quarrying activities; b) municipality boundaries and points of geological interest; c) Protected areas (no distinction made)*
around 910 *the country and finally d) High-value ecological zones for the inventory of significant taxa and potential future protection strategies.*



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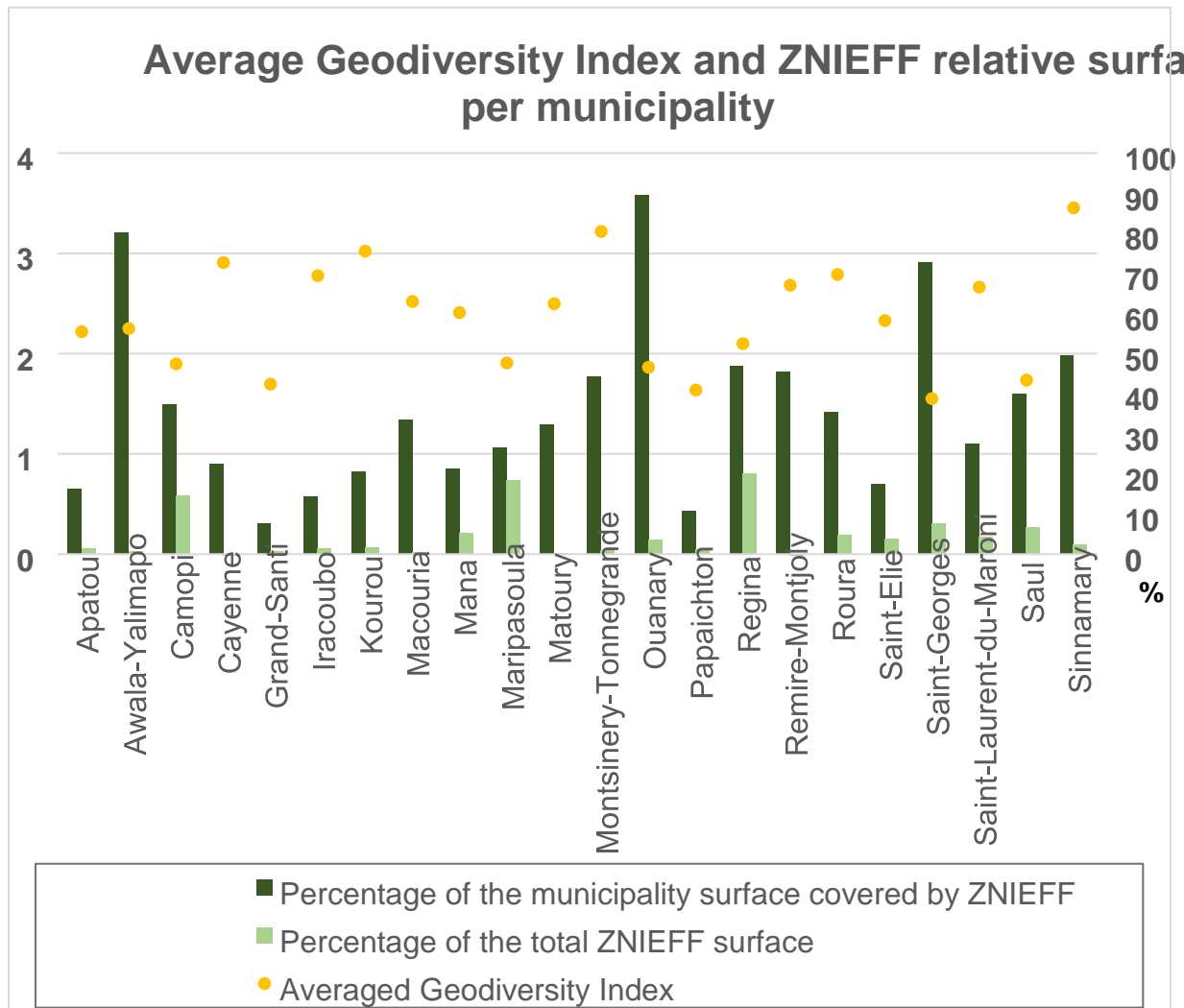
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Figure 8 Comparison of the geological maps of French Guiana at the scale of 1: 500,000 (used in this study) with cartographic renderings still under development at finer scales (i.e. 1: 100,000) and their impacts on lithodiversity sub-index In the sectors of Cayenne and Regina. Finer spatial data were confidentially provided by French National Survey for geological and mining research (BRGM).

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Figure 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.

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

