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1 From geodiversity to geofunctionality: quantifying geodiversity-based
2 ecosystem services for landscape planning in French Guiana

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23

24 Abstract

25 Geodiversity assessment gained a prominent interest in the geoscientific community and
26 beyond. However, it is not always sufficient for land planning or geoconservation. It is then
27 pivotal to account for the contribution of functional geodiversity (i.e. geofunctionality), for
28 instance declining the ecosystem services (ES) cascade model. However, by our knowledge
29 geodiversity-based ES (GES) have been rarely quantified.

30 This paper aims at adapting existing ES-related approaches to quantify and map GES in French
31 Guiana, a French Overseas territory located in the Amazon, where on-going land use changes
32 might affect ES supply. Seven GES were spatially assessed through an indicator-based approach
33 accounting for both offered and used GES and merged into multiservices maps. Multiservices
34 maps were then combined with a hemeroby index to highlight geofunctionality hotspots.
35 Difference maps were finally used to compare geodiversity and geofunctionality patterns.

36 The ES framework seems an effective way to quantitatively assess geofunctionality.
37 Geodiversity and geofunctionality do not follow the same spatial patterns: very geodiverse
38 areas can be poorly functional and vice-versa. Therefore, geodiversity and geofunctionality
39 need to be both considered when it comes to landscape planning. This might be enhanced
40 through hotspots mapping to highlight priority areas for planners. This study also focuses on
41 the role of human inputs in GES supply and raises questions about the selection of proper
42 indicators that should fit each step from the ES supply to management. High-quality datasets
43 must be available and their occasional absence is a central matter of land planning that must
44 be addressed before every decision-making process.

45 *Keywords:* Geodiversity, Ecosystem Services, Hotspots, Landscape, Human Inputs, French
46 Guiana

47

1. Introduction

49
50
51 Despite their pivotal role in socio-ecological functioning, abiotic and interfacial (i.e. soils)
52 components of natural diversity still tend to do not find their due place within land planning,
53 environmental management and conservation strategies (Brilha et al. 2018; Boothroyd and
54 McHenry 2019), which often focus mostly on biodiversity (Chakraborty and Gray 2020).
55 Such considerations converged within the development of geocological approaches (Tandaric
56 2015) and of the concept of “geodiversity”, as a new prism to look at all non-living components
57 of nature and as a new geological and geographical paradigm (Claudino-Sales 2021).
58 Geodiversity, abiotic equivalent of biodiversity (Gray 2011), is generally defined as “the natural
59 range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms,
60 topography, physical processes), soil and hydrological features,” including “their assemblages,
61 structures, systems and contributions to landscapes” (Gray 2013).
62 Despite its scope encompasses a wider range of activities included in land-planning (Serrano
63 and Ruiz-Flaño 2007; Schrodt et al. 2019), geodiversity has been mainly related to
64 geoconservation. The possibility, conditions and usefulness of a broader operationalization of
65 this concept need to be tested and demonstrated. Moreover, the assessment of geodiversity
66 in terms of site-specific richness and abundance (Zwolinski et al. 2018) appears insufficient to
67 support both land planning and geoconservation (Scammacca et al. 2022a). It is therefore
68 critical to apprehend the ensemble of contributions that geodiversity provides to socio-
69 ecological functioning (i.e. geofunctionality) (Volchko et al. 2020; Scammacca et al. 2023a).
70 Over the last years, the scientific community suggested that declining the “ecosystem services”
71 (ES) concept to geodiversity might be an effective way to assess such contributions (Kløve et al.
72 2011; Gray et al. 2013; Van der Meulen et al. 2016; Reverte et al. 2020; Volchko et al., 2020;
73 Carrión-Mero et al. 2022) and the role of geodiversity in the delivery of many ES has been
74 widely recognized (Gray, 2011; Van Ree et al. 2017; Fox et al. 2020; Crisp et al. 2021). ES can
75 be defined as the contributions that ecosystems provide to human well-being (Muller and
76 Burkhard 2012; Haines-Young and Potschin 2018), sometimes through human inputs (Jones et
77 al. 2016; La Notte et al. 2017) and which do not exist in isolation from people's needs, demand,
78 access and priorities (Haines-Young and Potschin 2010; Heink et al. 2016).
79 The ES approach, particularly because of its suitability to assessment and mapping exercises
80 (Martinez-Harms and Balvanera 2012; Burkhard and Maes 2017), is widely recognized as a

81 potential tool to improve environmental monitoring and land planning through holistic thinking
82 about ecosystem processes and human well-being (Wei and Zhan 2023). This might be
83 particularly useful in remarkable areas of natural richness and diversity such as the Amazon
84 basin, where rapid on-going land use changes affect ES supply (Richards and VanWey 2015;
85 Jakovac et al. 2016; Ferreira et al. 2021). Located in this region, the only continental French and
86 European Overseas territory of French Guiana has almost 96% of its surface covered by Amazon
87 rainforest. Although it is one of the least densely populated areas in the world, population
88 growth rate and the related needs in terms of infrastructures, agricultural supplies and
89 economic growth, are exacerbating, potentially affecting ES supply. Land use impacts on ES
90 supply are often analyzed through hotspots mapping, which also supports land planners in
91 geographic prioritization (Orsi et al. 2020). Analogously, hotspots can be used to identify highly
92 geodiverse and highly threatened areas (Bétard and Peulvast 2019).

93 Despite it might play a greater role than biotic components in the delivery of some services
94 (Heink et al. 2016; Slabbert et al. 2022), geodiversity has been often neglected in practice in
95 the developments of the ES concept. Although soil-related ES gained a growing interest over
96 the last decades (Baveye et al. 2016; Fossey et al. 2020; Scammacca et al., 2023b), geodiversity-
97 based ES (GES) are still considered as an “abiotic extension” (Gray, 2018) in current ES
98 classification systems (Van der Meulen et al. 2016), creating a dichotomy between the role of
99 biotic and abiotic contributions in ES supply (Fox et al. 2020).

100 By our knowledge, quantitative assessments of GES remain uncommon (Butorac and Buzjak
101 2020; Miklos et al. 2020; Reverte et al. 2020) and current studies provide often qualitative
102 assessments of GES and of their relationships with biodiversity and geodiversity (Alahuta et al.,
103 2018). Recently, Balaguer et al. (2023) applied the matrix-based approach to assess how land
104 use changes might affect ecosystem services provided by geodiversity in Brazil. Nevertheless,
105 the scarcity of quantitative studies might limit the full implementation of the geodiversity
106 concept within the ES framework towards the accomplishment of Sustainable Development
107 Goals (Van Ree and Van Beukening 2016; Brilha et al. 2018; Bitoun et al. 2022). French Guiana
108 geodiversity, despite it is historically associated to gold mining, played an important role in the
109 past dynamics of the region and it has a wider potential of contributing to the supply of multiple
110 ES (Scammacca et al. 2022a). Because of its socio-geo-ecological features, this territory
111 represents a major challenge for sustainable land planning and conservation (Aubertin and
112 Pons 2017; Budoc 2017). Previous studies focused on the assessment of ES in the region (Sieber

113 et al. 2021) mainly based on land-use proxies or specific biotic parameters (Trégarot et al.
114 2021).

115 This study has therefore the purpose to: i) attempt at a first quantification of geofunctionality
116 in French Guiana, in terms of GES supply; ii) analyze the spatial patterns of geodiversity and
117 geofunctionality and; iii) explore approaches to account for geodiversity and geofunctionality
118 within sustainable land planning strategies in French Guiana discussing the challenges of data
119 unavailability and the pertinence of potential ES management indicators.

120

2. Applying the ecosystem service cascade model to geodiversity

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122

123 The ES paradigm has been conceptualized through the “cascade model” which distinguishes
124 between ES components (e.g. ecosystem processes, functions, services, benefits) and linking
125 the two ends of ES supply chain (Haines-Young and Potschine 2010). This model has been often
126 revisited, particularly to fit land planning requirements (Villamagna et al. 2013; Von Haaren et
127 al. 2014; La Notte et al. 2017; Zhang et al. 2022). Von Haaren et al. (2014) re-adapted the
128 cascade model proposing a practice-oriented ES evaluation model identifying: “offered” ES (or
129 ES capacity), as the totality of ecosystem contributions that could, at least potentially, be
130 utilized by humans, and “used” ES (or ES flow) which are those currently utilized by humans
131 (Von Haaren et al. 2014).

132 This distinction might also offer complementary perspectives elucidating the aspect of human
133 inputs within planning objectives (Albert et al. 2016). Since landscapes are often modified by
134 societies, human-derived capital – in terms for instance of knowledge, human interventions
135 and environmental management (Fig.1) – is often necessary for the delivery of many ES (Jones
136 et al. 2016). However, this dimension is rarely considered in ES assessments and it is currently
137 unclear to what extent human influence is included in the ES concept (Heink et al. 2016).

138 In order to quantify GES, this study follows the Von Haaren et al. (2014) model. The link
139 between functions and services is reflected by the offered or used ES supply, depending on the
140 intensity of the human input involved (Fig. 1). On one hand, the assessment of offered ES
141 implies the acknowledgement (i.e. inventory, prospection, knowledge) of the capacity to
142 deliver the service according to user needs. On the other, the assessment of used ES might
143 imply human inputs involving planning and management practices (e.g. infrastructures
144 construction, exploitation, transformation, conservation) that allow for the offered service to
145 be concretely accessible and enjoyed by users according to their demands (Fig. 1).

146

3. Study area

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149 The current approach is tested in French Guiana, a French region located in South America (Fig.
150 2). Its geology, locally documented (Choubert 1949; Magnien et al. 1990) and described by the
151 scientific literature (Choubert 1974; Milesi et al. 2003; Théveniaut et al. 2012) can be framed
152 within the formation of the Precambrian terrains of the Guiana Shield (Delor et al. 2003). French
153 Guiana can be divided into two main geomorphological domains: i) the coastal plains of the
154 lowlands (4% of the territory), underlined by ancient and recent Quaternary sediments (Fig.
155 2a); ii) the uplands of the inner regions (96% of the territory), with moderate relief energy (e.g.
156 hills of granitic inselbergs and volcano-sedimentary peaks reaching a maximum of 850 meters
157 a.s.l.), and composed of outcrops of the oldest crystalline Paleoproterozoic basement formed
158 during the crustal growth of the Transamazonian orogeny (2.25-1.9 Ga) (e.g. metamorphic,
159 magmatic, sedimentary and volcanic rocks). Of particular interest, two greenstone belts, mainly
160 composed of meta-volcanic lithology with greenschist to amphibolite facies metamorphism
161 and of poorly known meta-volcano-sedimentary rocks (Fig 2a), host most of gold primary and
162 placer deposits, targeted by legal and illegal mining (Scammacca et al. 2022b). Water resources
163 are distributed among groundwater bodies (84,000 km² in confined aquifers) and a dense and
164 tufted network of surface waters (20,000 km of length) spread across the territory (DEAL,
165 2013). Soils are well documented although data are scattered and often non-harmonized. They
166 are greatly heterogeneous as a function of petro-geochemistry diversity of parent materials,
167 geomorphological structures, tectonics, weathering through time and hydrological dynamics
168 (Boulet 1979; Palvadeau 1999; Ferry et al. 2003). Lowland soils, developed on coastal plains
169 include moderately developed soils, Histosols, Gleysols, Podzols, while highland soils include
170 Ferralsols, ferric Cambisols, Acrisols, Plinthosols and Podzols (Leprun et al. 2001).

171 Human settlements and activities are mostly located along the coastal areas and along the
172 borders of Maroni and Oyapock rivers (Fig. 2b). Formal and informal human activities range
173 from artisanal, industrial (e.g. fishing, hunting, mining, space sector, manufacturing, energy,
174 agriculture, forestry) to commerce, construction, water management, tourism and transport.

175 French Guiana hosts more than 280,000 inhabitants in approximately 84,000 km² but with
176 the second highest population growth rate among French regions. With 96% of its surface
177 covered by the Amazon rainforest and 90% under State ownership (Iedom 2021), land tenure
178 is a major issue, leading to challenges for future land management and conservation strategies.

179 4. Materials and methods
180 4.1 Considered GES and indicators selection

181
182 Seven GES were selected in order to include the main ES classes (e.g. provisioning, regulating,
183 cultural services) and according to the significant planning and environmental challenges in
184 French Guiana. (Table 1): four provisioning services such as mineral commodities supply (MM),
185 non-metallic raw materials supply (MnM), surface water for drinking purposes (WS),
186 groundwater for drinking purposes (WU), two regulating and maintenance services such as
187 natural habitat regulation (HAB) and flood control (FC) and one cultural service, i.e. recreational
188 activities (GC).

189 GES were assessed in their offered and used dimensions and mapped firstly on a single-service
190 basis and then combined to obtain multi-services maps (Fig. 3). GES were assessed and mapped
191 through spatially explicit indicators selected according to existing studies (Fig. 4) and listed with
192 the related input data in Table 2. Abiotic indicators were specifically chosen to underline the
193 role of geodiversity in ES supply, sometimes in combination with human or social data. Input
194 data were collected on GIS-based platforms such as *GeoGuyane* and *Guyane SIG*. More details
195 are available in the Supplementary materials. Although their non-renewable character, raw
196 materials supply services (MM and MnM) were addressed because it might be significant in
197 landscape-oriented ES frameworks for planning perspectives (Kandziora et al. 2013), especially
198 in such areas of interest. Their offered dimension was assessed respectively based on
199 prospected mineral occurrences and lithological favorability (Fig. 4a and b) while the used
200 dimension was based on the location of legal mines and quarries (Grêt-Regamey and Weibel
201 2020 (Fig. 4h and i). Water supply services (WS and WU) were quantified based on the actual
202 good status of surface waters (Fig.4c) and aquifers location (Fig.4d) for their offered dimension
203 (Albert et al. 2016; Reverte et al. 2020) and on drinking water points for the used dimension
204 (Fig.4j and k). Landscape capacity to support biodiversity habitats (HAB) was assessed through
205 biodiversity potential levels described by Guitet et al. (2015a), which identify forest habitats
206 mainly based on geomorphology (Guitet et al. 2013), one of the main drivers of biodiversity
207 changes in the Amazon basin (Guitet et al. 2015b) (Fig.4e). The surface of protected areas
208 indicated the used dimension of the service (Fig.4l). Flood control (FC) was assessed based on
209 the presence of natural barriers such as wetlands (Kandziora et al. 2013) while flood-prone
210 areas were identified by Guitet and Brunaux (2017) through the HAND topographic algorithm

211 (Rennó et al. 2008) (Fig. 4f). The assessment of the used service was based on the location of
212 wetlands in areas covered by flood-risk prevention plans (Albert et al. 2016) (Fig. 4m).
213 Recreational activities offer (GC) was assessed according to the number of currently inventoried
214 geosites (Nontanovanh and Roig 2010; Roig and Moisan 2011; Bourbon and Roig 2013) and the
215 presence of outcrops of granitic inselbergs (Fig. 4g), considered as one of the uncommon ways
216 to observe French Guiana lithology (Ferry et al. 2003). The used dimension was characterized
217 integrating a distance parameter (Albert et al. 2016) between geosites and the road network
218 (Fig. 2n).

219

220 4.2 GES assessment and mapping

221

222 After initial data were pre-processed (Fig. 4) (e.g. data merging, data extraction, geometry
223 validation) using Qgis Desktop 3.28.5 and ArcMap 10.8.2 software, they were intersected, for
224 each GES, with a 10x10 km grid-cell layer covering the whole continental part of the study area
225 (922 cells).

226 Data were summarized according to each cell depending on the units of the initial data (Table
227 2). For instance, data expressed in units of surface (e.g. used MM, offered and used MnM,
228 offered WU, used HAB, offered and used FC), length (e.g. offered WS and usedGC) or volume
229 (e.g. MnM) were summed up for each cell while data expressed in terms of numbers of
230 punctual geometries were simply counted (e.g. offered MM andGC, used WS and WU).
231 Surfaces, lengths and point counting were calculated automatically using Qgis Desktop 3.28.5
232 functions. For the GC service, distances were calculated using the “Join attributes by nearest”
233 tool and then averaged for each cell.

234 Each service map was joined by attributes to the original cell-grid layer. The values expressed
235 for each service were re-classified in four classes using Jenks natural breaks, ranging from 1
236 (i.e., low supply) to 4 (i.e., very high supply).

237 The scores of offered and used single-service maps were summed to obtain multi-service maps
238 representing, respectively, total offered and used geofunctionality (*Gf*). *Gf* maps were re-
239 classified in four classes using Jenks natural breaks, ranging from 1 (i.e., low supply; sum equal
240 to 7) to 4 (i.e., very high supply; sum superior to 18)

241 All the final maps were interpolated through kriging on ArcMap 10.8.2 in order to limit border
242 effects, often caused by the homogenization of partial data contained in bordering cells.

243 4.3 Updating the Geodiversity Index (*Gt*)

244

245 The Geodiversity Index (*Gt*) for the study area was originally assessed by Scammacca et al.
246 (2022a), as the sum of four partial thematic sub-indices (e.g. lithological and unlithified
247 diversity, mineral diversity, hydrodiversity, and geomorphodiversity). The index was here
248 updated following two steps:

249 i) A pedodiversity sub-index, was integrated in the original assessment through a coarse
250 regional Soil Map of French Guiana (Blancaneaux 1979), recently available as a digital vector
251 layer with a spatial scale of 1:1,000,000.

252 ii) The hydrodiversity sub-index was recalculated using the same input data (e.g. surface
253 and underground waters) and counting the number of different entities in each cell. Surface
254 waters were categorized by their Strahler rank, as suggested by the 2019 Water Planning report
255 (OEG, 2020).

256

257 4. 4 GES and geodiversity relationships

258

259 The relationships between offered and used GES and between *Gf* and *Gt* levels were analyzed
260 through difference mapping. Changes in spatial patterns and levels were obtained by adding a
261 new field in the attribute table and calculating the relative difference (expressed in %) between
262 offered and used GES according to the following equation (Eq. 1):

$$263 \quad RD_{Gf} = 100 \frac{Gf_o - Gf_u}{Gf_o}$$

264

265 Where RD_{Gf} is the relative difference between offered (Gf_o) and used (Gf_u) geofunctionality.
266 Changes between total offered and potential *Gf* and *Gt* indices were calculated according to
267 the equation (Eq. 2):

268

$$269 \quad RD_{Gtf} = 100 \frac{Gt - Gf_{o,u}}{Gt}$$

270

271 Where RD_{Gtf} is the relative difference between the geodiversity index values *Gt* and offered
272 (Gf_o) and used (Gf_u) geofunctionality.

273 Spatial differences were classified on a range of seven classes translating the direction and the
274 intensity of the change: for difference maps related to offered and used GES, areas with
275 negative values infer that used GES levels are superior to offered GES levels while areas with
276 positive values infer that offered GES levels are superior to used GES levels. When the value is
277 equal to zero, offered and used GES show the same levels. The same considerations can be
278 applied to the maps of relative difference between total Gt and offered or used Gf (Eq. 3).

279

280 4.5 Geodiversity and geofunctionality hotspots

281

282 According to the approach proposed by Bétard and Peulvast (2019), a Threat Index (TI) was
283 combined to Gt in order to obtain a Sensitivity Index (SI) and highlight geodiversity hotspots. In
284 this study TI was assessed based on the Hemeroby “ M ” index (Steinhardt et al. 1999), which is
285 an integrative measure of human impacts on ecosystems (Lausch et al. 2015) and has the
286 advantage to be both ecologically well-founded and easily applicable (Frank et al. 2012). This
287 index is often used to evaluate the naturalness degree of an area (Walz 2008) and can be
288 integrated within the assessment of ecological functioning (Frank et al. 2012).

289 The index was calculated based on the Regional Land Use Plan (RLUP) of French Guiana (CTG
290 2016), at the scale of 1:100,000 as spatial input data. The RLUP defines the general allocation
291 of areas to given land uses according to predefined planning objectives. It divides the territory
292 in eleven land use categories (Fig. 5a) translating current and future activities. A Hemeroby
293 degree (Fig. 5b) was assigned to each land use category as suggested by Walz and Stein (2014),
294 (Table 3). Since the study area is cartographically divided in 922 cells with equal size, a simple
295 area-weighted Hemeroby index was calculated using the following equation (Eq. 3) (Walz and
296 Stein, 2014):

$$297 \quad M_w = \sum_{h=1}^n f_n \times h$$

298 Where M_w is the simple area-weighted Hemeroby index, n is the number of degrees of
299 Hemeroby (here: $n = 7$), f_n is the proportion (%) of category n , h is the degree of Hemeroby.
300 The calculation was performed intersecting the Hemeroby degree map (Fig.5b) with the original
301 grid layer. After summarizing the intersected values to the grid cells, Eq. 4 was applied. The TI
302 map was then interpolated through kriging showing low and high threat areas (Fig. 5d).

303 Finally, the SI was automatically obtained by the combination of the TI raster map with the *Gt*
304 raster map (Fig. 3) using ArcMap Raster Calculator tool and according to the equation (Eq. 4):

305

$$306 \quad SI_{GI} = TI \times Gt$$

307 The same equation was applied to offered and used *Gf* (*Gf_{o,u}*) raster maps as following (Eq. 5):

308

$$309 \quad SI_{GES} = TI \times Gf_{o,u}$$

310

311 The SI classes were normalized based on the overall minimum (i.e. 45.9) and maximum (i.e.
312 1,424.3) values of the three maps.

313

314 5. Results

315 5.1 GES levels and maps

316

317 Figure 6 shows the single-service offered (Fig. 6a to g) and used (Fig.6i to o) GES maps while
318 overall averaged GES levels are synthetized in Figure 7. Globally speaking, the results highlight:
319 i) some services which are generally largely used – in terms of exploitation, management or
320 conservation strategies – compared to their offer (e.g. MM, HAB, GC); ii) some services which
321 are mainly underused – which does not imply a necessity of use – such as MnM, WS, WU, FC;
322 iii) general sustainable uses with potential overuses of the resources (e.g. MM, HAB, GC) but
323 which must be analyzed very carefully according to the methodological choices and the
324 selected indicators.

325 Raw material supply for mining (MM) shows high offered levels along the two greenstone belts
326 (Fig. 6a), although used levels are only higher in the northern belt because of formal
327 interdictions in the southern one, where the Amazonian Park is located (Fig. 6i) and where
328 illegal gold mining is very active (Jébrak et al. 2021). MnM offered levels are higher in all the
329 Quaternary sedimentary formations of the coastal plain (Fig. 6b) – where used MnM levels are
330 mainly located (Fig. 6j) – and in the TTG units (Fig. 2a), particularly in the western area of the
331 territory. Water supply (e.g. WS and WU) and natural habitat regulation (i.e. HAB) are offered
332 almost in the whole study-area (Fig. 6c, d and e). WS and WU are only locally used along the
333 coastal and riverine regions (Fig. 6k and l) while HAB shows moderate to high levels in almost
334 the totality of the territory (Fig. 6m). Despite FC shows moderate levels throughout French
335 Guiana (Fig. 6f), used levels are mainly located in coastal areas (Fig. 6n). GC is supplied in specific
336 spots spread across the whole region (Fig. 6g), mainly in the coastal, eastern and southern
337 regions. The southern areas are less accessible and, therefore, show lower used levels (Fig. 6o).
338 Unlike all offered GES, which show overall higher levels with the exception of MM and GC (Gf_o
339 = 1.3), used GES display globally low levels (Fig. 7). Only HAB differences map highlights multiple
340 areas where offered levels are inferior to the used ones (Fig. 6u). Nevertheless, when averaged
341 over the whole study area, levels are higher for the offered HAB service ($Gf_o= 3$) than for the
342 used one ($Gf_o= 2.6$) (respectively Fig. 6h, p and x).

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5.2 Comparing Geodiversity (*Gt*) and geofunctionality (*Gf*) levels

Figure 8 compares the *Gt* (Fig. 8a) with offered and used *Gf* (Fig. 8b and c). Except for the northern and southern belts where *Gt* levels are at their peaks, *Gf* levels are higher than *Gt* levels (Figure 8d). Areas in the western part of French Guiana, characterized by TTG complexes (Fig. 6b) show higher offered *Gf* levels with relative differences compared to *Gt* that is locally higher than 100% (Fig. 8d). When averaged over the whole study area, offered *Gf* levels are approximately 55% higher than *Gt* levels.

On the contrary, considering the overall low used single-services levels (Fig. 7), Figure 8e highlights many areas where used *Gf* levels are estimated as lower than *Gt* levels. Nevertheless, when averaged over the whole study area, *Gt* levels are only 7% superior to used *Gf* levels (median equal to 0).

5.3 Geodiversity and geofunctionality hotspots

Most of the highest threat levels are located particularly along the coastal areas, where most of the human settlements and activities are located (Fig. 9a), with the highest peak of threats located particularly between the main cities of Cayenne and Kourou (Fig.5b). Moderate levels are also shown along the riverine areas of Maripasoula, when going upstream the Maroni River. When the TI map is combined with *Gt* (Fig. 9b) and offered (Fig. 9c) and used *Gf* (Fig. 9d), the highest levels of sensitivity (i.e. hotspots) are highlighted particularly for *Gt*, mainly along the coastal areas. *Gf* hotspots are less contrasted but still present particularly in the highest-threat areas on the coastal areas and along the Maroni River (Fig. 9c). Used *Gf* hotspots seem to follow similar patterns but, since used *Gf* levels are lower, the contrast is less enhanced (Fig. 9d).

376 6. Discussion

377

378 6.1 The added-value of geofunctionality assessment and hotspot analysis: from land
379 planning to landscape planning

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381 The assessment of geodiversity results often in the measurement of the heterogeneity of
382 landscapes abiotic features and it is generally influenced by their spatial geometry and
383 distribution within a given area. Switching to a functional dimension is uncontestably critical to
384 concretely enhance planning strategies because it allows to understand the complex
385 relationships between geodiversity-related entities and socio-ecological functioning, needs and
386 uses. As shown in Figures 8d and 8e, geodiversity and geofunctionality do not always follow the
387 same spatial patterns and thus, they must be both accounted when it comes to planning tasks.
388 Geofunctionality relates geodiversity to human activities, which can range from conservation
389 to exploitation or artificialization. Indeed, “land” planning might be defined as the systematic
390 and voluntary assessment of alternatives for land use and a territorial repartition of resources
391 reflecting socio-economic conditions, policy visions (e.g. economic development, landscape
392 protection, equal access to education and culture) and knowledge, in order to adopt the best
393 land use options (Metternicht 2017; Desjardins 2021). Since land uses and human inputs imply
394 a socio-economic and functional dimension of space and time, they dissolve within a “territorial
395 metabolism” (Desjardins, 2021) that goes beyond preservation and conservation purposes
396 alone, including also processes that might alter, exploit, artificialize, transform or even destroy
397 natural resources.

398 Therefore, “landscape” – rather than “land use”– planning implies a holistic and metabolic
399 vision of ecosystem diversity, in both its biotic and abiotic dimensions, and it allows the
400 understanding of the relationships between biodiversity, geodiversity and socio-ecological
401 functioning and needs.

402 Geodiversity and biodiversity should therefore be highlighted as equal and linked concepts (Ren
403 et al. 2021). Because geodiversity finds its synthesis in the landscape (Alexandrowicz and
404 Kozłowski 1999; Serrano and Ruiz-Flaño 2007), its operationalization should encompass the
405 landscape seen as a multifunctional complex unit (Nin et al. 2016; Englund et al. 2017;
406 Metternicht 2017; Miklós et al. 2020). Despite it raises many debates (Schröter et al. 2014), the
407 ES concept appears to be an interesting approach to analyze and assess geofunctionality. This
408 landscape-oriented analysis undoubtedly involves spatialized approaches to identify the

409 distribution, across space, of landscape functional units. When it comes to such assessments,
410 it is preferable to distinguish between GES or SI levels when averaged over the whole study
411 area and their spatial distribution. Although considering the study area as a whole entity with
412 averaged levels might be helpful to support strategies at the national or supranational scales,
413 it would not allow to identify clusters or priority areas of intervention at the landscape
414 functional unit scale.

415 For instance, despite averaged low levels, MM supply shows high offered levels mainly along
416 the two greenstone belts, which host most of the gold deposits (Fig. 4a). Offered WS and WU
417 are spread along the whole region (Fig. 4c and d) confirming the fact that, as its name suggests,
418 *Guyana* is the “land of many waters” (Clifford 2011). The Quaternary formations of the coastal
419 areas underlaying the Paleoproterozoic basement offer for instance overlapping aquifers,
420 increasing known offered WU levels in such regions (Fig. 7d). These portions of the territory
421 show also the most important potential in hosting natural flood-prone areas and wetlands (Fig.
422 4f), mainly because of their intertidal positions, the potential influence of sedimentary aquifers
423 and the presence of mangrove ecosystems developed on the coastal sediments.

424 When geofunctionality is combined with human-related threats according to the approach
425 proposed by Bétard and Peulvast, (2019), geofunctionality hotspots maps provide information
426 about the spatial patterns of endangered areas, thus supporting the spatial allocation of lands,
427 priorities of intervention, while integrating the socio-environmental impacts and conflicts with
428 other potential land uses (Nin et al. 2016). Important information could be also added through
429 statistical analysis or generalized additive models to analyze the relationships between land use
430 intensity, geodiversity and geofunctionality as performed by Tukianen et al. (2017). Focusing
431 only on geodiversity hotspots, would neglect potential areas of ordinary abiotic nature or lower
432 geodiversity that are not necessarily less important in terms of ES supply (Bétard and Peulvast
433 2019).

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6.2 The dual role of human inputs in supplying services: towards ES management indicators?

440 Land use, as a human footprint on the environment, is often used to proxy threats to ecological
441 integrity. Nevertheless, the conceptualization of land use only as a “threat” would be limiting
442 in terms of landscape analysis since it is one of the main drivers of landscape structures and
443 patterns (Pătru-Stupariu et al. 2017), driven by governance objectives and societal needs
444 (Galler et al. 2016). As mentioned and conceptualized by the revised cascade model, human
445 inputs are considered as a part of the ES production chain.

446 A service relates to a demand and it is indeed often combined with built, human or social capital
447 in terms of inventory and/or management activities (Jones et al. 2016). This can be particularly
448 observed in two complementary dimensions of GES supply. For instance, the supply of raw
449 materials for mining (MM) and quarrying (MnM) implies, on one hand, the construction of
450 exploitation infrastructures and human workforce that are able to provide the final service. On
451 the other hand, the location of the supply related to such activities is often regulated by
452 mandatory frameworks, such as the Quarrying Regional Plan (QRP) or the Departmental Mining
453 Plan (DMP) in French Guiana, which state where extraction can or cannot take place according
454 to different criteria (e.g. sensitive areas, minimum distance to populated areas). Also, MnM
455 levels are often concentrated especially along the coastal strips (Fig. 4j), since the sandy,
456 lateritic and hard-rock materials are more accessible and closer to human settlements where
457 on-going construction projects are located (Fig. 4j). Surface and groundwater supplies are often
458 located next to populated areas (Fig. 4k and l), since the used service would be non-existent
459 otherwise. Access to geoheritage areas is provided by a network of roads except for the
460 southern areas of French Guiana, where environmental protection measures limit some human
461 interventions (Fig. 4o). Globally, the highest levels of used geofunctionality seem to follow
462 human population distribution, suggesting that the concept of “used” service, depending on
463 the type of service, might be tightly related to human activities requiring interventions other
464 than conservation.

465 Thus, human inputs might act as ES co-producers and as ES managers. In the first case, they will
466 particularly influence the future levels of offered service supply, while in the second case they
467 might control ES spatial patterns, in both cases, to satisfy a demand.

468 In French Guiana, ES management seems to lead a clear distinction between two areas. The
469 first one is composed of the littoral – and, in some case, riverine – areas, the most inhabited
470 ones where most of needs and ES demands are located but also where geodiversity and
471 biodiversity levels seem higher, hosting dynamic and fragile landscapes (e.g. mangroves,
472 wetlands). The second area embraces most of the inner regions of the territory where human
473 density is very low and where habitat protection strategies dominate, sometimes in contrast
474 with dispersed legal or illegal gold mining activities.

475 Protected areas show in some cases even higher “used” levels than “offered” ones (Fig. 4m and
476 u). The overall higher values for this service and the spatial mismatches between its offered
477 and used levels, might imply that land planners give a priority to biodiversity conservation
478 objectives in inner French Guiana, compared to other land uses. In such protected areas, which
479 are also considered by the DMP, land uses such as mining are therefore forbidden because
480 conflictual with the objectives of local and national strategies. This might explain for instance
481 the difference between offered and used MM levels in the gold deposits of the southern
482 greenstone belt (Fig.6 q). It must not be forgotten indeed that the supply of multiple ES
483 depends on their management and it can result in synergies and trade-offs between single
484 services. For instance, management strategies targeting MM or MnM supply could lead to
485 decreasing surface or groundwater supply, because of the widely known impacts of extraction
486 activities on water quality (Castello and Macedo 2016) and quantity (Northey et al. 2019).
487 However, such considerations should highlight the existence of informal and illegal activities,
488 such as illegal gold mining, which participate to the production of “used” services – for instance
489 in the southern greenstone belt – but increasing negative impacts and trade-offs with other
490 services (e.g. water quality, natural habitat support). The inclusion of informal human inputs
491 and the related fuzzy-data should be considered in such approaches.

492 For better implementations within landscape planning, indicators selection should then fit the
493 cascade model and it might be necessary to clearly distinguish between offered services
494 indicators, used services indicators and management indicators. As example, Rendon et al.
495 (2022) propose a list of non-regulatory management indicators to analyze pressures on soil-
496 related ES, mainly in terms of agricultural practices, although management indicators should
497 cover all the dimensions of human inputs. Table 4 attempts to satisfy such distinction for further
498 improvements of the current study proposing a list of management indicators and their
499 objectives for the services considered in this study. Management indicators could vary in terms

500 of management “intensity”, which can range from preliminary screening, inventory and
501 baseline data acquisition, to advanced tasks of land allocation, zoning and planning. Such
502 indicators, sometimes unlike the ES they are related to, tend to be complementary rather than
503 discordant. For instance, management tools related to mining and water planning are often
504 compatible and harmonized. In French Guiana, the DMP and the SDAGE (Table 4) are explicitly
505 supportive and interrelated between each other. Management indicators, ideally, should be
506 the result of adequate strategies where planners accounted for ES synergies and trade-offs so
507 to find the optimal balance between economic development and ecological integrity.
508 Thus, a true implementation of the ES framework would require in practice “formal changes of
509 existing planning instruments” (Albert et al. 2016) and it would be therefore pivotal to address
510 in the future all the dimensions of human inputs in ES production chain to support prospective
511 studies for ES assessment, monitoring and landscape planning.
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6.3 Unavailable data are a matter of landscape planning

516 Human inputs include the inventory of data that can be provided by all the stakeholders in a
517 territory (Jones et al. 2016), through various methods and tools, to supply the baseline of
518 knowledge used to quantify the capacity of an ecosystem to provide a service. Therefore, the
519 quality of such data and their scales of acquisition drive ES assessment and mapping tasks and
520 have a critical impact on the final results. Most of the services do not display the same spatial
521 coverage and are limited only to few portions of the study area. If this is related, on one hand,
522 to the bio-geo-physical heterogeneity of the landscape – meaning clearly that not all the ES are
523 or can be supplied by the same spatial units and might have different patterns – on the other
524 hand, it gives clues about data availability, accessibility and data acquisition methods (Le
525 Tourneau and Noucher 2023).

526 For instance, the assessment of quarrying and mining materials supply does not account for
527 data on ancient quarries which sometimes were located in the newly populated areas nor on
528 illegal gold mining production rates and risks. Raw materials offered supply is here based on
529 geological surveys and prospections carried by the French National Geological Survey over the
530 last decades (Magnien et al. 1990; Billa et al. 2013) that specifically targeted the gold-hosting
531 regions of the greenstone belts (Fig. 6a). Potential wetlands were identified at the scale of the
532 whole region (Guitet and Brunaux 2017). Biodiversity-related data (e.g. Fig. 4e) are mapped at
533 the regional scale also because most of the surveys over the years focused on biotic resource
534 inventory (Gautreau 2020). Spatial patterns of geoheritage points can be explained by their
535 identification through both remote-sensed regional data and local field surveys.

536 The areas with highest ES levels are located on the coastal and riverine areas of French Guiana,
537 because they are the most explored, accessible and inhabited and data are needed for most of
538 the past and current practical planning challenges. These areas are also the most threatened
539 (Fig. 9a), since human occupation is mainly located here and, based on our assessment, that
540 automatically leads to “very high” sensitivity levels (Fig. 9b, c, d).

541 This means also that applying land use-based metrics for threats identification – such as the
542 Hemeroby index – could translate spatial bias and overlaps in the identification of
543 geofunctionality hotspots since: i) land use is one of the drivers of used ES supply; ii) land use
544 can proxy the accessibility and availability of data, which might be higher in anthropic areas.

545 The relationship between the spatial distribution of data availability and inhabited areas might
546 lead to underestimate the levels of offered services in more remote areas. Such
547 underestimations should be considered as a loss of opportunity to develop potential services
548 which are still not known, and consequently unused, or, on the contrary, as the best way to
549 preserve them (i.e. since they are not known they might be also not degraded by human
550 interventions).

551 Unavailability of geoscientific data must be identified and assessed and such gaps represent an
552 undeniable challenge to address for landscape-planning. Through indirect or direct measures,
553 the landscape and its structures should be better acknowledged to identify and apply adequate
554 indicators for ES assessment and management. In lack of adequate indicators, the assessment
555 process risks to be performed with coarse available data since it is the only option, rather than
556 the best one. This is particularly true for regulating services, which provide direct impacts that
557 can be difficult to express through pertinent indicators (Villamagna et al. 20213), unlike
558 provisioning services which are usually more easily available. Therefore, the multi-service
559 combination of ES of different natures could lead to bias, since it combines services assessed
560 based on data that have different levels of availability.

561 A Regional Commission for Geoheritage of French Guiana has been only recently established
562 and geoinventories are still ongoing. Geodiversity features of French Guiana, such as the unique
563 komatiitic-related *Dachine* diamonds (Smith et al. 2016), a great variety of inselbergs spread
564 across the region (Aertgeerts 2020), such as the *Mamilihpann* inselberg and its still unknown
565 cave paintings (Fuentes 2022) or else the remarkable *Grand Connétable* island could be
566 integrated in the assessment of cultural GES. Wetland identification field surveys are still
567 unaccomplished because of the lack of harmonized soil and vegetation data (Blum 2013). Also,
568 water-related services could be proxied by the permeability of lithological formations (Perotti
569 et al., 2019) for instance through hydraulic conductivity or rock porosity (Freeze and Cherry,
570 1979).

571 The identification of management goals and land planning exercises require an important level
572 of detail, especially at regional and local scales (Gomez-Zotano et al. 2018). As highlighted by
573 Heink et al. (2016), indicator choice “should capture the meaning of the construct that is to be
574 measured” and “the variance between the indicator and the *indicandum* should be low”,
575 meaning that the conceptual model used should be as clear as possible and that indicator
576 selection should stick to it.

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578 6.4 Abiotic services or abiotic indicators?

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580 In a theoretical way, the ES concept already includes abiotic and interfacial components in its
581 definition. However, the current position of geodiversity within the ES framework still remains
582 confused (Fox et al. 2020). This declination resulted sometimes in varying classification systems
583 and terminologies (e.g. “subsurface services”: Van Ree and Van Beukening 2016; “abiotic ES”:
584 Fox et al. 2020; “geosystem services”: Gray 2011). For instance, some authors suggest that
585 *geosystem services* are all the services associated with geodiversity and that are “independent
586 of interactions with biotic nature” (Fox et al. 2020). Nevertheless, if we consider the landscape
587 as a unified, holistic and dynamic whole, most of the services are *per se* the result of both biotic
588 and abiotic components of natural diversity. One might argue that in any case, attention should
589 be given to identifying a given biotic or abiotic factor that plays a dominant role in the supply
590 of a specific service. Nevertheless, this dominance should be rather expressed in how that
591 specific service is assessed, and thus, in the choice of an adequate predictive – and dominant –
592 variable to assess it. For instance, although the “offered” services selected in this study are
593 classified as biotic (e.g. HAB, FC) and abiotic (MM, MnM, WS, WU, GC) (Table 1), their
594 assessment was performed only according to abiotic variables. Thus, it is pivotal to distinguish
595 between the services themselves (biotic and abiotic) and the underpinning variable(s) that can
596 be selected as assessment indicators. In other words, a unified definition of geodiversity-based
597 ES might be needed.

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600 Conclusion

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602 To fully support land use planning and conservation objectives, it is fundamental to account for
603 the contribution of geodiversity to socio-ecological functioning (i.e. geofunctionality). This
604 study proposes an approach to assess geofunctionality in terms of geodiversity-based
605 ecosystem services (GES), through a conceptual model – based on the revised ES cascade model
606 which distinguishes between offered and used services – and a methodological framework that
607 aims at identifying and comparing geodiversity and geofunctionality hotspots.

608 The application of these frameworks in French Guiana, an Overseas French territory presenting
609 planning and conservation challenges, highlights the feasibility of such approaches and the
610 heterogeneity of spatial patterns between geodiversity and geofunctionality which thus must
611 be both included within landscape planning.

612 When assessing typological and functional variability, it is pivotal to distinguish between levels
613 and spatial patterns. The choice between the types of results to consider strictly depends on
614 the objectives of the assessment. Spatialized approaches seem more adequate for planning,
615 seen as the process of allocating lands and integrating impacts and conflicts with other
616 potential land uses. Nevertheless, when assessing geofunctionality hotspots – since used
617 services rely here on human inputs – threats and used geofunctionality levels might overlap
618 and lead to spatial bias. According to this study, French Guiana can be divided in two main
619 areas: the littoral areas, more populated, with higher levels of geodiversity and used
620 geofunctionality but also higher threats, and the less inhabited and less known inner regions,
621 a widest area with important assessed levels of offered geofunctionality.

622 Despite the revised ES cascade model includes human interventions in the supply of ES, further
623 improvements should focus on a clear-cut distinction of human inputs as ES co-producers,
624 managers but also demanders.

625 Indicator selection is a crucial step in the assessment process and it should satisfy multiple
626 criteria and fit precisely the conceptual model used. However, data unavailability is the main
627 issue in the achievement of such requirements and it must therefore be considered as a matter
628 of land planning that should be quantified. This is particularly true in French Guiana, where
629 geoscientific data production must be enhanced.

630 Landscape planning – rather than “land use planning” – implies a holistic and metabolic vision
631 of ecosystem diversity, in both its biotic and abiotic dimensions, and it allows the understanding
632 of the relationships between biodiversity, geodiversity and socio-ecological functioning and
633 needs. The ES concept, despite its anthropocentric nature, can be a useful tool to identify and
634 analyze human-nature relationships. However, many improvements must be achieved to clarify
635 the ES concept itself, the place of abiotic and interfacial components of natural diversity within
636 it, and how this concept can fully relate to human activities, uses, needs and priorities of action
637 to drive and support the implementation of policies in increasingly disturbed environments.

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639

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647

648 Compliance with Ethical Standards and ethical conduct

649 The authors declare that the presented research has been carried in compliance with the
650 Ethical Standards proposed by the journal *Geoheritage* and Springer and they declare to comply
651 with the ethical responsibilities of authors.

652

653 Conflict of Interest

654 The authors declare that they have no known competing financial interests or personal
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