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ORIGINAL ARTICLE

From Geodiversity to Geofunctionality: Quantifying Geodiversity-Based Ecosystem Services for Landscape Planning in French Guiana

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Abstract

Geodiversity assessment gained a prominent interest in the geoscientific community and beyond. However, it is not always sufficient for land planning or geoconservation. It is then pivotal to account for the contribution of functional geodiversity (i.e., geofunctionality), for instance declining the ecosystem services (ES) cascade model. However, by our knowledge, geodiversity-based ES (GES) have been rarely quantified. This paper aims to adapt existing ES-related approaches to quantify and map GES in French Guiana, a French Overseas territory located in the Amazon, where ongoing land use changes might affect ES supply. Seven GES were spatially assessed through an indicator-based approach accounting for both offered and used GES and merged into multiservice maps. Multiservice maps were then combined with a hemeroby index to highlight geofunctionality hotspots. Difference maps were finally used to compare geodiversity and geofunctionality patterns. The ES framework seems an effective way to quantitatively assess geofunctionality. Geodiversity and geofunctionality do not follow the same spatial patterns: very geodiverse areas can be poorly functional and vice-versa. Therefore, geodiversity and geofunctionality need to be both considered when it comes to landscape planning. This might be enhanced through hotspot mapping to highlight priority areas for planners. This study also focuses on the role of human inputs in GES supply and raises questions about the selection of proper indicators that should fit each step from the ES supply to management. High-quality datasets must be available and their occasional absence is a central matter of land planning that must be addressed before every decision-making process.

Keywords Geodiversity · Ecosystem services · Hotspots · Landscape · Human inputs · French Guiana

Introduction

Despite their pivotal role in socio-ecological functioning, abiotic and interfacial (i.e., soils) components of natural diversity still tend not to find their due place within land planning, environmental management, and conservation strategies (Brilha et al. 2018; Boothroyd and McHenry 2019), which often focus mostly on biodiversity (Chakraborty and Gray 2020).

Such considerations converged within the development of geoecological approaches (Tandarić 2015) and of the concept of "geodiversity," as a new prism to look at all non-living components of nature and as a new geological and geographical paradigm (Claudino-Sales 2021). Geodiversity, the abiotic equivalent of biodiversity (Gray 2011), is generally defined as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms,

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

Despite its scope encompassing a wider range of activities included in land-planning (Serrano and Ruiz-Flaño 2007; Schrodt et al. 2019), geodiversity has been mainly related to geoconservation. The possibility, conditions, and usefulness of a broader operationalization of this concept need to be tested and demonstrated. Moreover, the assessment of geodiversity in terms of site-specific richness and abundance (Zwoliński et al. 2018) appears insufficient to support both land planning and geoconservation (Scammacca et al. 2022a). It is therefore critical to apprehend the ensemble of contributions that geodiversity provides to socio-ecological functioning (i.e., geofunctionality) (Volchko et al. 2020; Scammacca et al. 2023a).

Over the last years, the scientific community suggested that declining the "ecosystem services" (ES) concept to geodiversity might be an effective way to assess such contributions (Kløve et al. 2011; Gray et al. 2013; Van der Meulen et al. 2016; Reverte et al. 2020; Volchko et al. 2020; Carrión-Mero et al. 2022), and the role of geodiversity in the delivery of many ES has been widely recognized (Gray 2011; Van Ree et al. 2017; Fox et al. 2020; Crisp et al. 2021). ES can be defined as the contributions that ecosystems provide to human well-being (Müller and Burkhard 2012; Haines-Young and Potschin-Young 2018), sometimes through human inputs (Jones et al. 2016; La Notte et al. 2017) and which do not exist in isolation from people's needs, demand, access, and priorities (Haines-Young and Potschin 2010; Heink et al. 2016).

The ES approach, particularly because of its suitability for assessment and mapping exercises (Martínez-Harms and Balvanera 2012; Burkhard and Maes 2017), is widely recognized as a potential tool to improve environmental monitoring and land planning through holistic thinking about ecosystem processes and human well-being (Wei and Zhan 2023). This might be particularly useful in remarkable areas of natural richness and diversity such as the Amazon basin, where rapid ongoing land use changes affect ES supply (Richards and VanWey 2015; Jakovac et al. 2016; Ferreira et al. 2021). Located in this region, the only continental French and European Overseas territory of French Guiana has almost 96% of its surface covered by the Amazon rainforest. Although it is one of the least densely populated areas in the world, the population growth rate and the related needs in terms of infrastructures, agricultural supplies, and economic growth are exacerbating and potentially affecting ES supply. Land use impacts on ES supply can be analyzed through hotspot mapping, which also supports land planners in geographic prioritization (Orsi et al. 2020). Analogously, hotspots can be used to identify highly geodiverse and highly threatened areas (Bétard and Peulvast 2019).

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

By our knowledge, quantitative assessments of GES remain uncommon (Butorac and Buzjak 2020; Miklós et al. 2020; Reverte et al. 2020) and current studies provide often qualitative assessments of GES and of their relationships with biodiversity and geodiversity (Alahuhta et al. 2018). Recently, Balaguer et al. (2023) applied a matrix-based approach to assess how land use changes might affect ecosystem services provided by geodiversity in Brazil. Nervertheless, the scarcity of quantitative studies might limit the full implementation of the geodiversity concept within the ES framework towards the accomplishment of sustainable development goals (Van Ree and van Beukering 2016; Brilha et al. 2018; Bitoun et al. 2023). French Guiana geodiversity, despite being historically associated with gold mining, played an important role in the past dynamics of the region, and it has a wider potential to contribute to the supply of multiple ES (Scammacca et al. 2022a). Because of its socio-geo-ecological features, this territory represents a major challenge for sustainable land planning and conservation (Aubertin and Pons 2017; Budoc 2017). Previous studies focused on the assessment of ES in the region (Sieber et al. 2021) mainly based on land-use proxies or specific biotic parameters (Trégarot et al. 2021).

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

Applying the Ecosystem Service Cascade Model to Geodiversity

The ES paradigm has been conceptualized through the "cascade model" which distinguishes between ES components (e.g., ecosystem processes, functions, services, benefits) and links the two ends of the ES supply chain (Haines-Young and Potschin 2010). This model has been often revisited, particularly to fit land planning requirements (Villamagna et al.

2013; Von Haaren et al. 2014; La Notte et al. 2017; Zhang et al. 2022). Von Haaren et al. (2014) re-adapted the cascade model proposing a practice-oriented ES evaluation model identifying: "offered" ES (or ES capacity), as the totality of ecosystem contributions that could, at least potentially, be utilized by humans, and "used" ES (or ES flow), which are those currently utilized by humans (Von Haaren et al. 2014).

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

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

Study Area

The current approach is tested in French Guiana, a French region located in South America (Fig. 2). Its geology, locally documented (Choubert 1949; Magnien et al. 1990) and described by the scientific literature (Choubert 1974; Milesi et al. 2003; Théveniaut et al. 2012), can be framed within the formation of the Precambrian terrains of the Guiana Shield (Delor et al. 2003). French Guiana can be divided into two main geomorphological domains: (i) the coastal plains of the lowlands (4% of the territory), underlined by ancient and recent Quaternary sediments (Fig. 2a); (ii) the uplands of the inner regions (96% of the territory), with moderate relief energy (e.g., hills of granitic inselbergs and volcano-sedimentary peaks reaching a maximum of 850 m a.s.l.), and composed of outcrops of the oldest crystalline Paleoproterozoic basement formed during the crustal growth of the Transamazonian orogeny (2.25–1.9 Ga) (e.g., metamorphic, magmatic, sedimentary, and volcanic rocks). Of particular interest, two greenstone belts, mainly composed of meta-volcanic lithology with greenschist to amphibolite facies metamorphism and of poorly known meta-volcano-sedimentary rocks (Fig 2a), host most of gold primary and placer deposits, targeted by legal and illegal mining (Scammacca et al. 2022b). Water resources are distributed among groundwater bodies (84,000 km^2 in confined aquifers) and a dense and tufted network of surface waters (20,000 km of length) spread across the territory (Guyane 2013). Soils are well documented, although data are scattered and often non-harmonized. They are greatly heterogeneous as a function of petro-geochemistry diversity of parent materials, geomorphological structures, tectonics, weathering through time, and hydrological dynamics (Boulet et al. 1979; Palvadeau 1998; Ferry et al. 2003). Lowland soils, developed on coastal plains, include moderately developed soils, Histosols, Gleysols, Podzols, while highland soils include Ferralsols, ferric Cambisols, Acrisols, Plinthosols, and Podzols (Leprun et al. 2001).

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

French Guiana hosts more than 280,000 inhabitants approximately 84,000 km^2 but with the second-highest population growth rate among French regions. With 96% of its surface covered by the Amazon rainforest and 90% under State ownership (Iedom 2021), land tenure is a major issue, leading to challenges for future land management and conservation strategies.

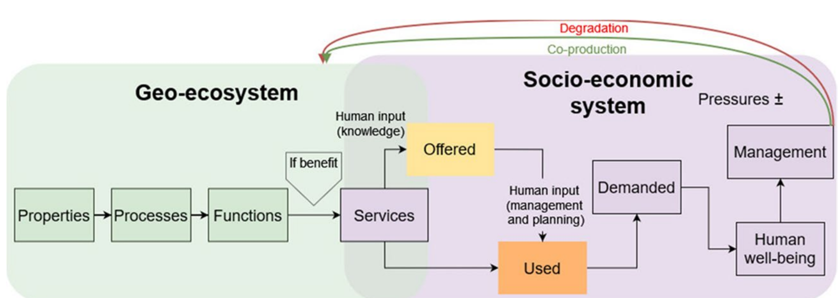

Fig. 1 Simplified revised cascade model of ecosystem services according to the modifications proposed by Von Haaren et al. (2014) and Albert et al. (2016)

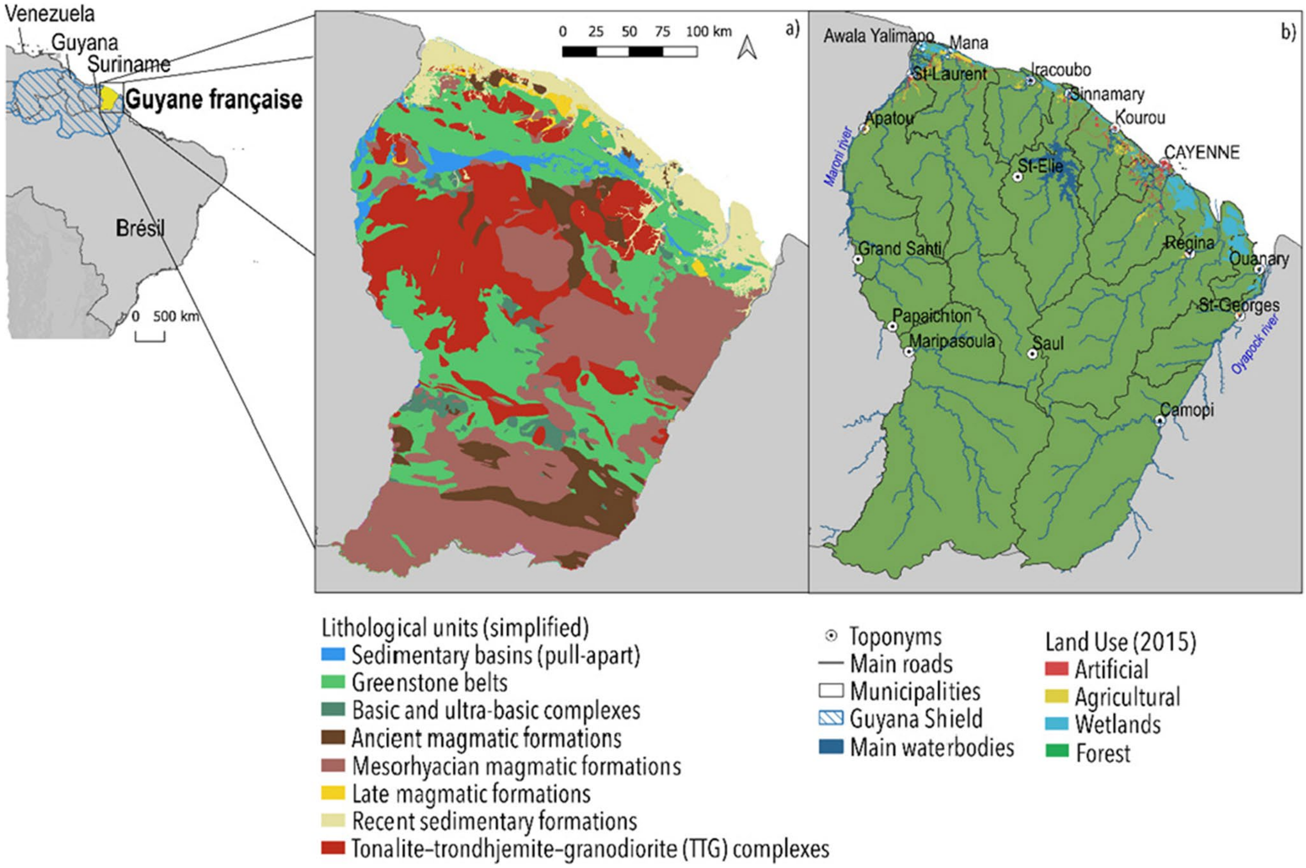

Fig. 2 Location of the study area and simplified geological map of French Guiana (**a**) and land use patterns (**b**)

Materials and Methods

Considered GES and Indicators Selection

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

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

Table 1 List of the seven considered GES and their correspondences in the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin-Young 2018)

Acronym	Description	CICES Section	CICES Division	CICES Group	CICES Class	CICES code	Satisfied SDGs
MM	Raw material supply for mining	Provisioning	Non-aqueous natural abiotic ecosystem outputs	Mineral substances used for nutrition, materials or energy	Mineral substances used for material purposes	4.3.1.2	8, 9
MnM	Raw material supply for quarrying	Provisioning	Non-aqueous natural abiotic ecosystem outputs	Mineral substances used for nutrition, materials or energy	Mineral substances used for material purposes	4.3.1.2	8,9,11
WS	Drinking surface water supply	Provisioning	Water	Surface water used for nutrition, materials or energy	Surface water for drinking	4.2.1.1	3, 6, 14
WU	Drinking groundwater supply	Provisioning	Water	Ground water for used for nutrition, materials or energy	Ground (and subsurface) water for drinking	4.2.2.1	3, 6, 14
HAB	Natural habitat regulation	Regulation & Maintenance	Regulation of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	Maintaining nursery populations and habitats (Including gene pool protection)	2.2.2.3	11, 13, 14, 15
FC	Flood control	Regulation & Maintenance	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	2.2.1.3	3, 6, 13
GC	Recreational activities	Cultural	Direct, in-situ, and outdoor interactions with natural physical systems that depend on presence in the environmental setting	Physical and experiential interactions with natural abiotic components of the environment	Natural, abiotic characteristics of nature that enable active or passive physical and experiential interactions	6.1.1.1	3,4,12

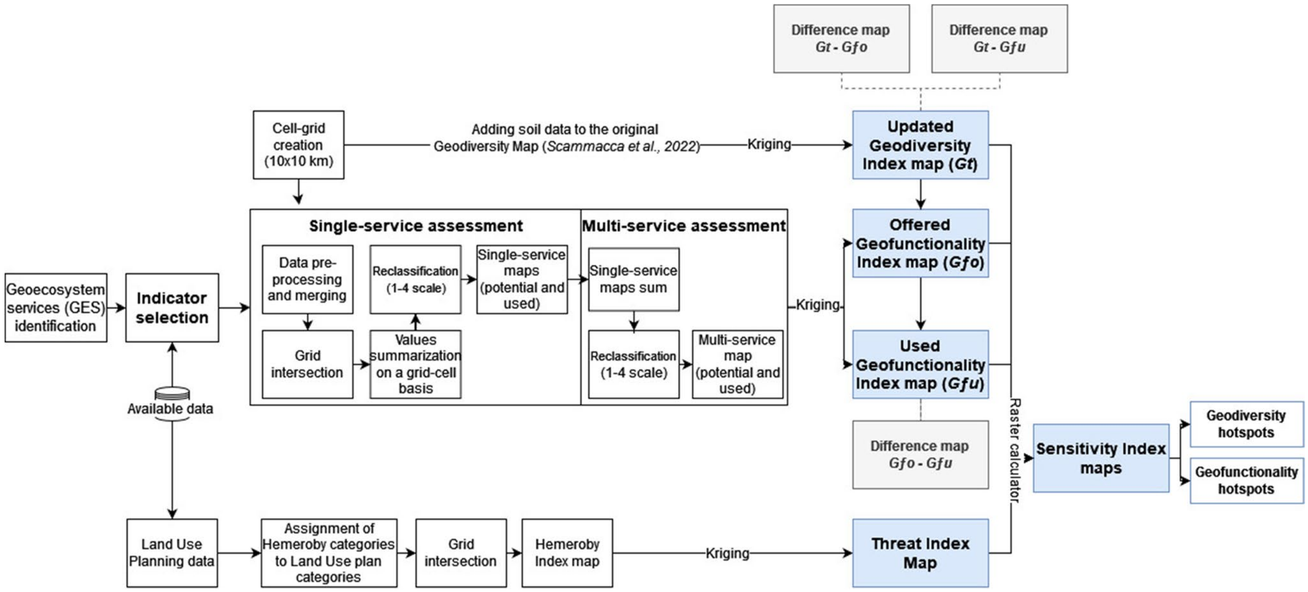

Fig. 3 Flowsheet of the methodology used in this study to perform a single-service and multi-services assessment of GES in French Guiana. Geofunctionality and geodiversity were combined to compare their levels and spatial patterns and then merged with land-use data to obtain hotspot maps

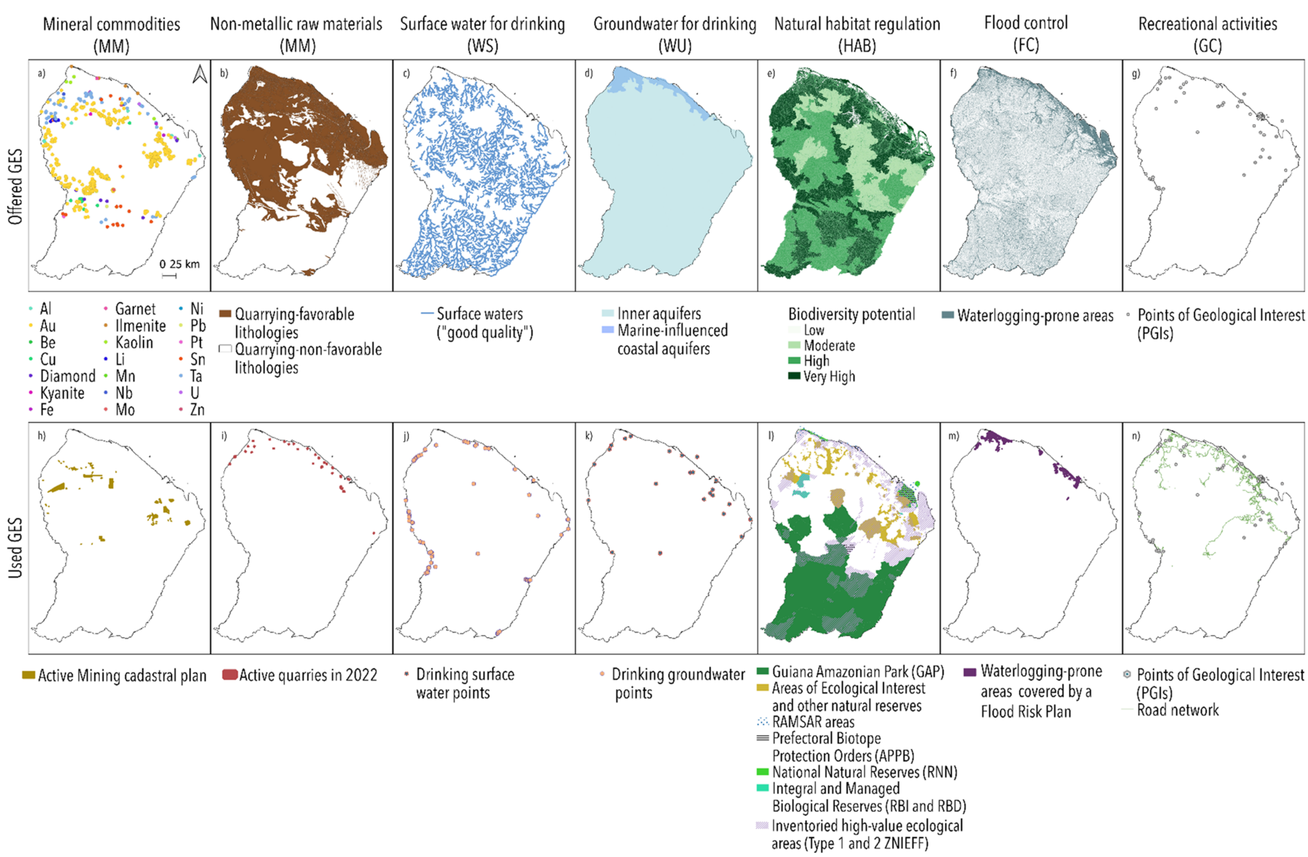

Fig. 4 Initial spatial data used for both offered and used GES. More details are available in Table 2 and in Supplementary Materials

Table 2 Indicators chosen for the assessment of each offered and used GES. The detailed list is available in Supplementary Materials

	Code	Indicator	Unit before scoring	Raw data	Spatial accuracy
Offered service	MM	Mineral deposits	Number per cell	Mineral occurrencies and prospections map	n/a
				Placer deposit prospection map	n/a
	MnM	Favorable geological areas	km^2 per cell	Geological Map of French Guiana	1; 500,000
				Quarrying Cadastral Plan map	n/a
	WS	Surface water quality	km per cell	2020–2027 objectives for surface water resource management map	1; 5000
	WU	Underground water body surface	km per cell	Undeground water bodies in inner lithological formations	1; 500,000
				Undeground water bodies affected by littoral dynamics	1; 500,000
	HAB	Biodiversity potential of natural habitats	km^2 per cell	Forest habitat catalog of French Guiana report	1; 200,000
	FC	Waterlogging-prone areas	km^2 per cell	Predictive identification of wetlands map within forest management	1; 5000
	GC	Geoheritage potential	Number per cell	Inselberg map	1; 1,000,000
				Georeferenced map of inventoried Points of Geological Interest	n/a
Used service	MM	Exploited mineral deposits	km^2 per cell	Mining cadastral plan map (CAMINO)	n/a
	MnM	Material production capacity	t/year	Extractive and quarrying activities map (excluding activities with permits expired in 2022)	1; 50,000
	WS	Surface water points	Number per cell	Drinking water points (only surface water)	1; 25,000
	WU	Underground water points	Number per cell	Drinking water points (only underground water)	1; 25,000
	HAB	Total protected areas	km^2 per cell	Ramsar wetland map	1; 500,000
				Guiana Amazonian Park (GAP)	1; 50,000
				Integral and Managed Biological Reserves (RBI and RBD)	1; 50,000
				National Forestry Office zoning (only including Areas of Ecological Interest, Natural Reserves and Areas and Landscapes under Physical and General Protection)	1; 50,000
				National Natural Reserves (RNN)	1; 500,000
				Type 1 ZNIEFF map	1; 50,000
				Type 2 ZNIEFF map	1; 50,000
				Prefectorial order for protection of the biotope (APB)	1; 25,000
	FC	Flood-risk management	km^2 per cell	Plan for Flood Risk Prevention map	1; 25,000
				Predictive identification of wetlands map within forest management	1; 5000
	GC	Geoheritage accessibility	m	Inselberg map	1; 1,000,000
				Georeferenced map of inventoried Points of Geological Interest	n/a
				Road map of French Guiana	n/a

presence of natural barriers such as wetlands (Kandziora et al. 2013) while flood-prone areas were identified by Guitet and Brunaux (2017) through the HAND topographic algorithm (Rennó et al. 2008) (Fig. 4f). The assessment of the used service was based on the location of wetlands in areas covered by flood-risk prevention plans (Albert et al. 2016) (Fig. 4m).

Recreational activities offer (GC) was assessed according to the number of currently inventoried geosites (Nontanovanh and Roig 2010; Roig and Moisan 2011; Bourbon and Roig 2013) and the presence of outcrops of granitic inselbergs (Fig. 4g), considered one of the uncommon ways to observe French Guiana lithology (Ferry et al. 2003). The used dimension was characterized by integrating a distance parameter (Albert et al. 2016) between geosites and the road network (Fig. 2n).

GES Assessment and Mapping

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

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

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

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

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

Updating the Geodiversity Index (Gt)

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

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

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

GES and Geodiversity Relationships

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

$$\mathrm{RD_{Gf}} = 100\frac{\mathrm{Gf_o} - \mathrm{Gf_u}}{\mathrm{Gf_o}} \tag{1}$$

where $\mathrm{RD_{Gf}}$ is the relative difference between offered ($\mathrm{Gf_o}$) and used ($\mathrm{Gf_u}$) geofunctionality. Changes between total offered and potential Gf and Gt indices were calculated according to the equation (Eq. 2):

$$\mathrm{RD_{Gtf}} = 100\frac{\mathrm{Gt} - \mathrm{Gf_{o,u}}}{\mathrm{Gt}} \tag{2}$$

where $\mathrm{RD_{Gtf}}$ is the relative difference between the geodiversity index values Gt and offered ($\mathrm{Gf_o}$) and used (Gf_u) geofunctionality.

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

Geodiversity and Geofunctionality Hotspots

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

The index was calculated based on the Regional Land Use Plan (RLUP) of French Guiana (CTG 2016), at the scale of 1:100,000 as spatial input data. The RLUP defines the general allocation of areas to given land uses according to predefined planning objectives. It divides the territory into 11 land use categories (Fig. 5a) translating current and future activities. A Hemeroby degree (Fig. 5b) was assigned to each land use category as suggested by Walz and Stein (2014), (Table 3). Since the study area is cartographically divided into 922 cells of equal size, a simple area-weighted Hemeroby index was calculated using the following equation (Eq. 3) (Walz and Stein 2014):

$$M_w = \sum_{h=1}^{n} f_n \times h \tag{3}$$

where M_w is the simple area-weighted Hemeroby index, n is the number of degrees of Hemeroby (here, $n = 7$), f_n is the proportion (%) of category n, and h is the degree of Hemeroby.

The calculation was performed by intersecting the Hemeroby degree map (Fig. 5b) with the original grid layer. After summarizing the intersected values to the grid cells, Eq. 4 was applied. The TI map was then interpolated through kriging showing low- and high-threat areas (Fig. 5d).

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

$$SI_{GI} = TI \times Gt \tag{4}$$

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

$$SI_{GES} = TI \times Gf_{o,u} \tag{5}$$

The SI classes were normalized based on the overall minimum (i.e., 45.9) and maximum (i.e., 1424.3) values of the three maps.

Results

GES Levels and Maps

Figure 6 shows the single-service offered (Fig. 6a–g) and used (Fig. 6i–o) GES maps while overall averaged GES levels are synthetized in Fig. 7. Globally speaking, the results highlight the following: (i) some services which are generally largely used—in terms of exploitation, management, or conservation strategies—compared to their offer (e.g., MM, HAB, GC); (ii) some services which are mainly under-used—which does not imply a necessity of use—such as MnM, WS, WU, and FC; (iii) general sustainable uses with

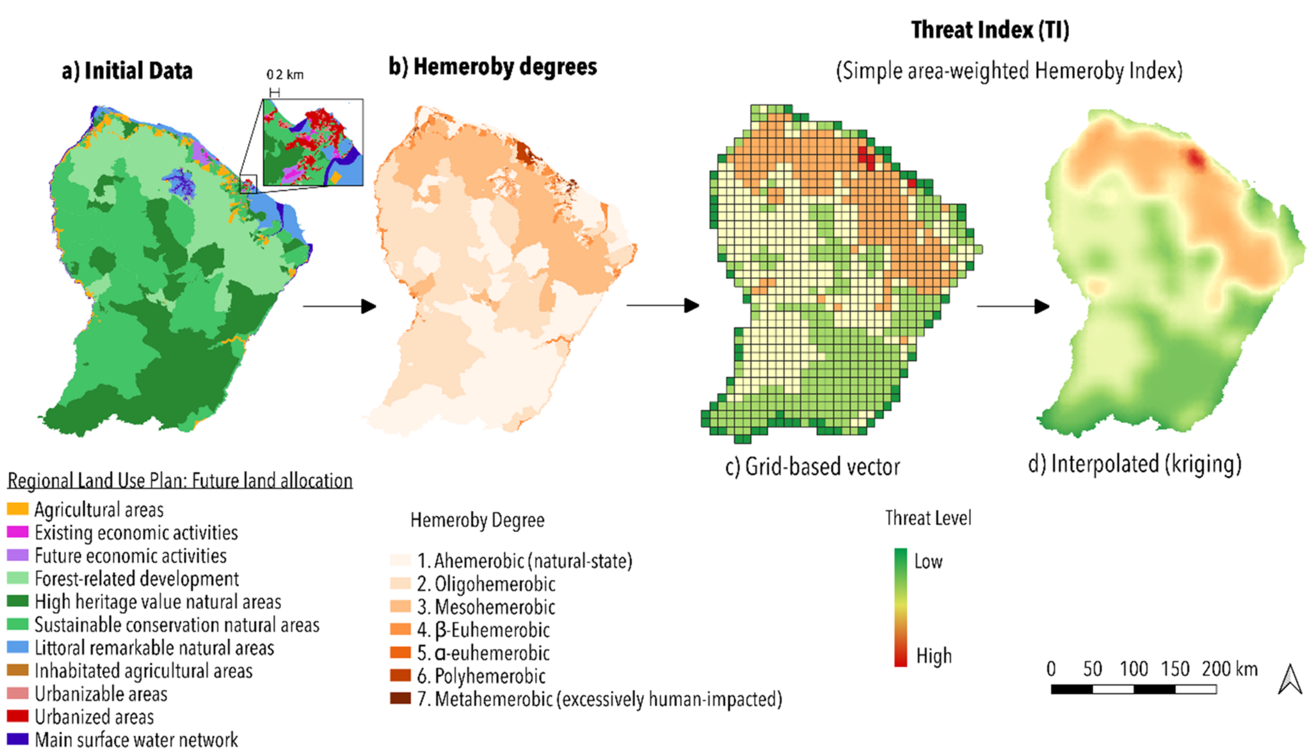

Fig. 5 Assessment of the threat index using the Hemeroby index formula proposed by Walz and Stein (2014)

Table 3 Association between Hemeroby degrees and land use categories

Degree	Name	Description	Assigned Corine land cover classes (Waltz and Stein, 2014)	Assigned Land allocation categories in the RLUP (French Guiana)	Hypothesis
1	Ahemerobic	Almost no human impacts	Bare rocks, Glaciers and perpetual snow	High heritage value natural areas; Littoral remarkable natural areas	No or very low influence of the economic dimension
2	Oligohemerobic	Weak human impacts	Broad-leaved, coniferous, mixed forests (PNV), salt marshes, intertidal flats, coastal lagoons, estuaries, sea and ocean	Sustainable conservation natural areas	
3	Mesohemerobic	Moderate human impacts	Coniferous and mixed forests (not PNV), transitional woodland-shrub, sparsely vegetated areas, burnt areas, natural grasslands, moors and heathland	Forest-related development areas	Moderate influence of the economic dimension
4	β-Euhemerobic	Moderate-strong human impacts	Green urban areas, pastures, water courses, water bodies, land principally occupied by agriculture, with significant areas of natural vegetation	Agricultural areas; main surface water network	
5	α-euhemerobic	Strong human impacts	Sport and leisure facilities, vineyards, non-irrigated arable land, complex cultivation patterns, fruit trees and berry plantations	Populated agricultural areas	Predominant influence of the economic dimension
6	Polyhemerobic	Very strong human impacts	Discontinuous urban fabric, mineral extraction sites, construction sites, dump sites	Urbanizable areas; future economic activities	
7	Metahemerobic	Excessively strong human impacts	Continuous urban fabric, industrial or commercial units, road and rail networks and associated land, port areas, airports	Urbanized areas; existing economic activities	

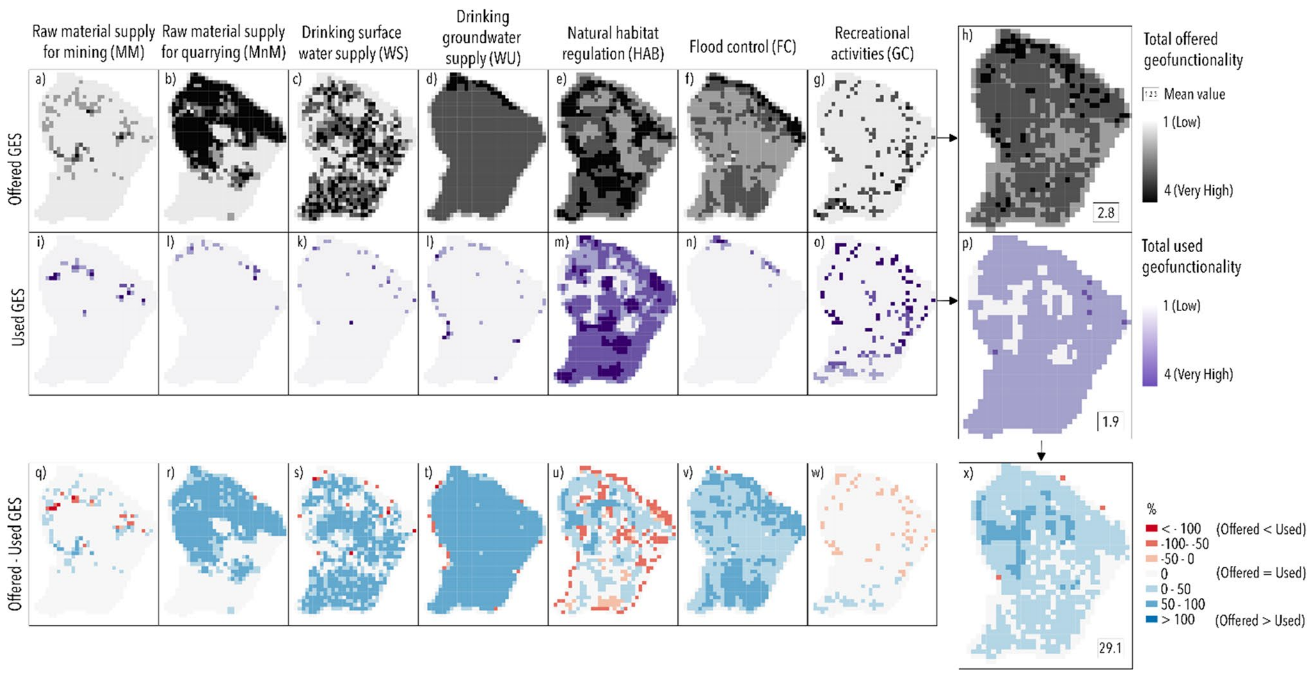

Fig. 6 Assessment and mapping of the selected GES in their offered (**a–h**) and used (**i–p**) dimensions. **h** and **p** are, respectively, the offered and used multi-service map. The offered and used dimensions of the assessed GES were then compared (**q–x**)

potential overuses of the resources (e.g., MM, HAB, GC) but which must be analyzed very carefully according to the methodological choices and the selected indicators.

Raw material supply for mining (MM) shows high offered levels along the two greenstone belts (Fig. 6a), although used levels are only higher in the northern belt because of formal interdictions in the southern one, where the Amazonian Park is located (Fig. 6i) and where illegal gold mining is very active (Jébrak et al. 2021). MnM-offered levels are higher in all the Quaternary sedimentary formations of the coastal plain (Fig. 6b)—where used MnM levels are mainly located (Fig. 6j)—and in the TTG units (Fig. 2a), particularly in the western area of the territory. Water supply (e.g., WS and WU) and natural habitat regulation (i.e., HAB) are offered almost in the whole study area (Fig. 6c–e). WS and WU are only locally used along the coastal and riverine regions (Fig. 6k and l) while HAB shows moderate to high levels in almost the totality of the territory (Fig. 6m). Despite FC showing moderate levels throughout French Guiana (Fig. 6f), used levels are mainly located in coastal areas (Fig. 6n). GC is supplied in specific spots spread across the whole region (Fig. 6g), mainly in the coastal, eastern, and southern regions. The southern areas are less accessible and, therefore, show lower used levels (Fig. 6o).

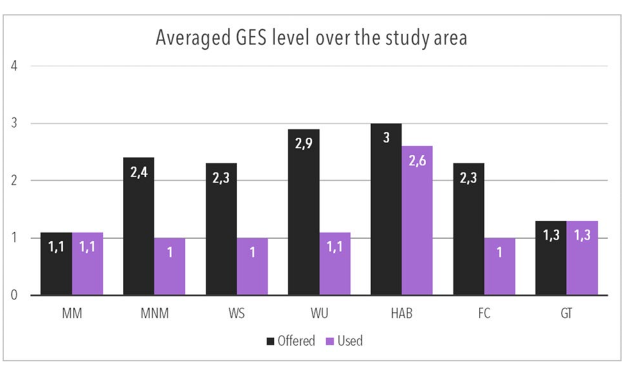

Fig. 7 Averaged offered (black) and used (purple) GES levels over the study area

Unlike all offered GES, which show overall higher levels with the exception of MM and GC ($Gf_o = 1.3$), used GES display globally low levels (Fig. 7). Only the HAB difference map highlights multiple areas where offered levels are inferior to the used ones (Fig. 6u). Nevertheless, when averaged over the whole study area, levels are higher for the offered HAB service ($Gf_o = 3$) than for the used one ($Gf_o = 2.6$) (respectively, Fig. 6h, p, and x).

Comparing Geodiversity (Gt) and Geofunctionality (Gf) Levels

Figure 8 compares the Gt (Fig. 8a) with the 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

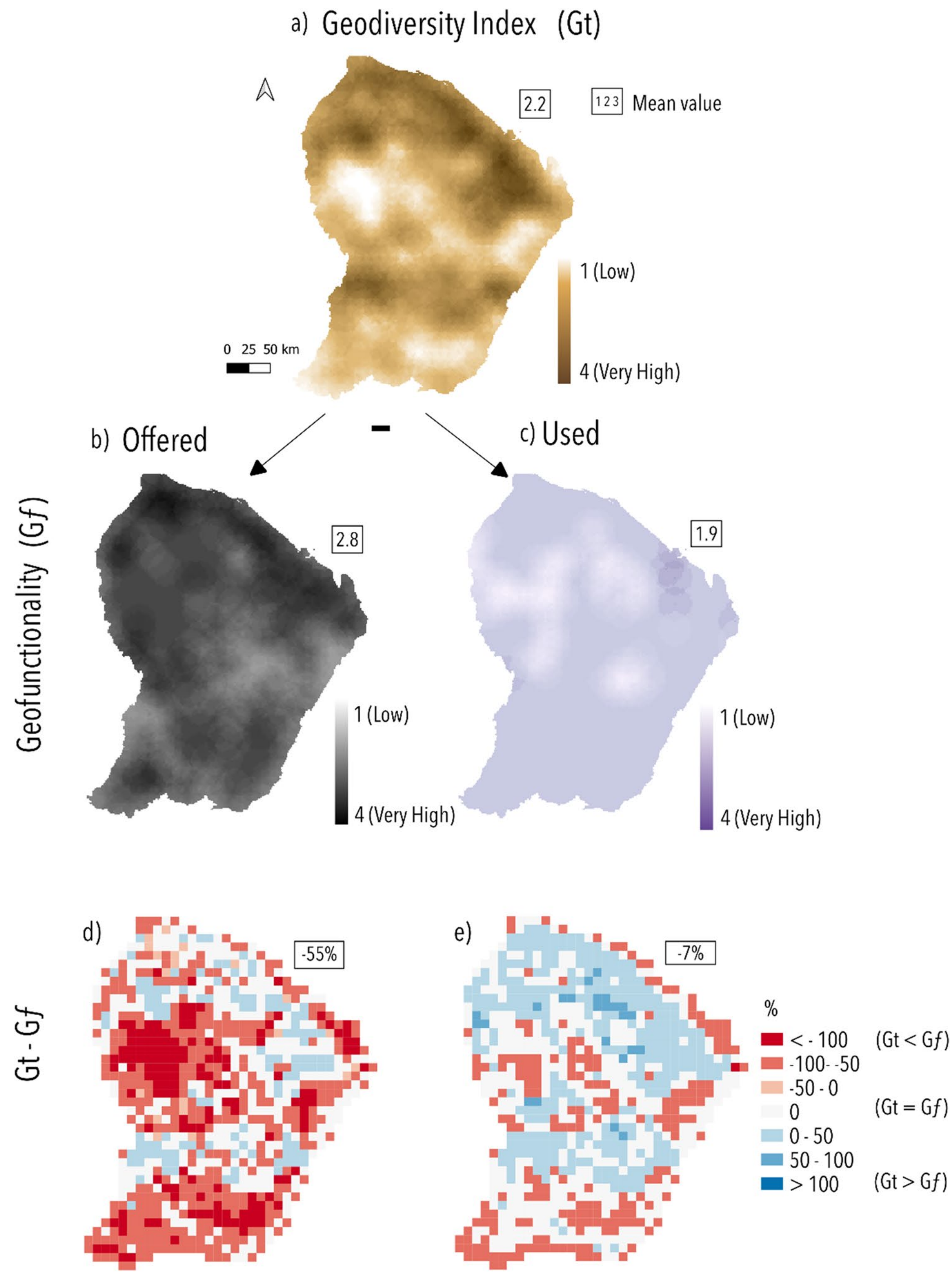

Fig. 8 Comparing geodiversity (**a**) and geofunctionality (**b**, **c**) indexes to obtain difference maps about their levels and spatial patterns

(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 approximatively 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).

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

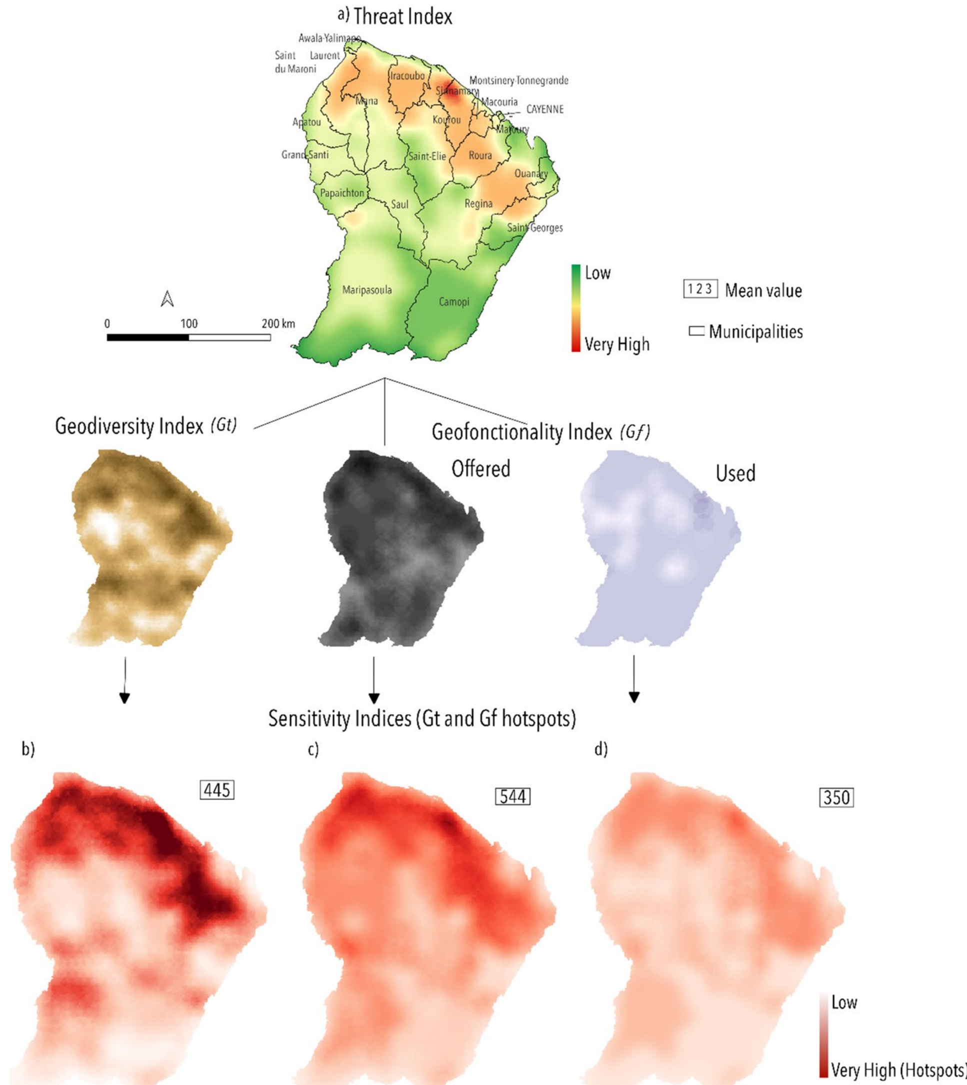

Fig. 9 Combination of the threat index (**a**) with geodiversity and geofunctionality indexes to obtain geodiversity hotspots (**b**) and geofunctionality hotspots (**c**, **d**)

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).

Discussion

The Added-Value of Geofunctionality Assessment and Hotspot Analysis: from Land Planning to Landscape Planning

The assessment of geodiversity results often in the measurement of the heterogeneity of landscape abiotic features, and it is generally influenced by their spatial geometry and distribution within a given area. Switching to a functional dimension is uncontestably critical to concretely enhance planning strategies because it allows to understand the complex relationships between geodiversity-related entities and socio-ecological functioning, needs, and uses. As shown in Fig. 8d and e, geodiversity and geofunctionality do not always follow the same spatial patterns, and thus, they must be both accounted for when it comes to planning tasks.

Geofunctionality relates geodiversity to human activities, which can range from conservation to exploitation or artificialization. Indeed, "land" planning might be defined as the systematic and voluntary assessment of alternatives for land use and a territorial repartition of resources reflecting socio-economic conditions, policy visions (e.g., economic development, landscape protection, equal access to education and culture), and knowledge in order to adopt the best land use options (Metternicht 2017; Desjardins 2021). Since land uses and human inputs imply a socio-economic and functional dimension of space and time, they dissolve within a "territorial metabolism" (Desjardins 2021) that goes beyond preservation and conservation purposes alone, including also processes that might alter, exploit, artificialize, transform, or even destroy natural resources.

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

Geodiversity and biodiversity should therefore be highlighted as equal and linked concepts (Ren et al. 2021). Because geodiversity finds its synthesis in the landscape (Alexandrowicz and Kozlowski 1999; Serrano and Ruiz-Flaño 2007), its operationalization should encompass the landscape seen as a multifunctional complex unit (Nin et al. 2016; Englund et al. 2017; Metternicht 2017; Miklós et al. 2020). Despite it raising many debates (Schröter et al. 2014), the ES concept appears to be an interesting approach to analyze and assess geofunctionality. This landscape-oriented analysis undoubtedly involves spatialized approaches to identify the distribution, across space, of landscape functional units. When it comes to such assessments, it is preferable to distinguish between GES or SI levels when averaged over the whole study area and their spatial distribution. Although considering the study area as a whole entity with averaged levels might be helpful to support strategies at the national or supranational scales, it would not allow to identify clusters or priority areas of intervention at the landscape functional unit scale.

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

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

The Dual Role of Human Inputs in Supplying Services: Towards ES Management Indicators?

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

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

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

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

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

For better implementations within landscape planning, indicator selection should then fit the cascade model, and it might be necessary to clearly distinguish between offered service indicators, used service indicators, and management indicators. As for example, Rendon et al. (2022) propose a list of non-regulatory management indicators to analyze pressures on soil-related ES, mainly in terms of agricultural practices, although management indicators should cover all the dimensions of human inputs. Table 4 attempts to satisfy such distinction for further improvements of the current study proposing a list of management indicators and their objectives for the services considered in this study. Management indicators could vary in terms of management "intensity," which can range from preliminary screening, inventory, and baseline data acquisition to advanced tasks of land allocation, zoning, and planning. Such indicators, sometimes unlike the ES they are related to, tend to be complementary rather than discordant. For instance, management tools related to mining and water planning are often compatible and harmonized. In French Guiana, the DMP and the SDAGE (Table 4) are explicitly supportive and interrelated between each other. Management indicators, ideally, should be the result of adequate strategies where planners accounted for ES synergies and trade-offs to find the optimal balance between economic development and ecological integrity.

Thus, a true implementation of the ES framework would require in practice "formal changes of existing planning instruments" (Albert et al. 2016), and it would be therefore pivotal to address in the future all the dimensions of human inputs in ES production chain to support prospective studies for ES assessment, monitoring, and landscape planning.

Unavailable Data Are a Matter of Landscape Planning

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

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

Table 4 Examples of management indicators that could be applied to the GES assessed in the present study their management scale and objectives

Management indicator	Type	French acronym	Description	Management scale	UICN category[a]	Management objectives	Related GES
Mineral exploration	Inventory	n.a.	Defines geological deposits of interest, approximating viable reserves	Project site, region	n.a.	Mineral deposit identification	MM
Departmental Mining Plan	Management	SDOM	Defines the general conditions for implanting mining sites and for their prospection, exploitation through a zoning based on the sensitivity of specific areas and their compatibility with mining	Region, department	n.a.	Mining zoning	
Regional Quarrying Plan	Management	SRC	Defines the general conditions for implanting quarries and all the orientations related to the logistical requirements of quarrying. It enables the inventory of resources, the prospective analysis of future demand in materials	Region	n.a.	Quarrying zoning and resource estimation	MnM
Master Plan for Water Development and Management	Management	SDAGE	Defines orientations and water-related objectives—water quality and quantity—to be satisfied by planning and zoning tools	Water catchment	n.a.	Identification, screening and monitoring of water resources and their chemical and ecological state	WS, WU
Natural Park (Guiana Amazonian Park)	Management	PAG	Defines national areas of natural, cultural, and landscape heritage to preserve and manage them on a large scale. In the "buffer zone," priority is given to heritage, species, and landscape protection (regulatory protection) while in the other areas, limited activities can be performed if ecological processes are maintained (contractual protection)	National	Ia, II, V	Scientific research Ecosystem protection Recreational activities Protection of terrestrial and aquatic landscapes	HAB

Table 4 (continued)

Management indicator	Type	French acronym	Description	Management scale	UICN category[a]	Management objectives	Related GES
French Guiana Regional Park	Management	PNRG	Area that has willingly decided to develop the territory based on economic and social development, natural, historical, cultural, landscape heritage protection, contributing to drive urban planning, communicating with the public and civil society, experimenting new forms of public and collective activities	Region	V	Recreational activities Protection of terrestrial and aquatic landscapes	HAB
Integral and Managed Biological Reserves	Management	RBI, RBD	Defines protected areas in forest or forest-like environments to preserve remarkable or representative habitats. They are "Managed" where priority is given to maintaining natural habitats and species in a given areas. They area "Integral" when priority is given to protect biodiversity, landscape, geomorphological and geological features and where human impacts, or research activities, are strictly monitored	n.a.	Ia, IV	Scientific research Conservation with potential interventions	HAB
Hunting and wild fauna national reserves	Management	RNCFS	Regulatory areas aiming at the study and conservation of wild game, mammals and birds. Hunting is forbidden except for general interest	National	Ib, IV	Protection of wild resources Conservation with potential interventions	HAB
Areas of ecological interest, natural reserves, and areas and landscapes under physical and general protection)	Management	n.a.	Define forested areas for natural habitats and natural diversity, drinking water sources, embankments, landscapes and ecological continuums preservation in avoidance of human pressures	Biogeographical region, forest management area, exploitation plot	n.a.	Zoning of forest areas of ecological interest	HAB

Table 4 (continued)

Management indicator	Type	French acronym	Description	Management scale	UICN category[a]	Management objectives	Related GES
National Natural Reserves	Management	RNN	Long-term tools for the protection of rare or representative spaces, species, geological objects, functional landscapes and biological diversity. They allow stakeholders concertation and can imply rehabilitation measures according to conservation objectives	National	Ia, III, IV	Scientific research Ecosystem protection preservation of specific natural entities Conservation with potential interventions	HAB, GC
Ramsar-protected areas	Inventory	n.a.	Identifies wetlands of international reconnaissance	International	III	Preservation of specific natural entities	HAB
High-value ecological zones for inventory	Inventory	ZNIEFF	Identifies and describes areas with high ecological interest for hosting biodiversity and natural heritage, to support scientific research and decision-making (e.g., conservation, land planning)	National	n.a.	Inventory of areas with high ecological interest	HAB
Prefectorial order for protection of the biotope	Management	APB	Enables regulatory protection and maintenance of important ecological habitats	Department	III, IV	Preservation of specific natural entities Conservation with potential interventions	HAB
Flood Risk Prevention Plan	Management	n.a.	Delimitates areas exposed to flooding risks so as to implement proscription and prevention measures (to avoid risk consequences or their aggravation) or proactive measures	Department, Region	n.a.	Risk zoning and assessment	FC
Points of Geological Interest	Inventory	n.a.	Areas with scientific, esthetical, and cultural values identified through the National Inventory of Geoheritage	Department	III	Preservation of specific natural entities	GC
Geotope prefectoral protection	Management	APG	Proposes a zoning to protect points of geological interests identified in a given area, forbidding the destruction, degradation, or modification of such sites or of the elements (e.g., fossils, minerals, rocks) composing them	Department, Region	III, IV	Preservation of specific natural entities Conservation with potential interventions	GC

Table 4 (continued)

Management indicator	Type	French acronym	Description	Management scale	UICN category[a]	Management objectives	Related GES
Geopark	Management	n.a.	UNESCO label to identify areas with high geoheritage values and enabling protection and valorization (e.g., local development and education)	International	III	Preservation of specific natural entities	GC

[a]UICN category is related to World Conservation Union categories to identify protected areas

points can be explained by their identification through both remote-sensed regional data and local field surveys.

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

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

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

Unavailability of geoscientific data must be identified and assessed, and such gaps represent an undeniable challenge to address for landscape planning. Through indirect or direct measures, the landscape and its structures should be better acknowledged to identify and apply adequate indicators for ES assessment and management. In the lack of adequate indicators, the assessment process risks to be performed with coarse available data since it is the only option, rather than the best one. This is particularly true for regulating services, which provide direct impacts that can be difficult to express through pertinent indicators (Villamagna et al. 2013), unlike provisioning services which are usually more easily available. Therefore, the multi-service combination of ES of different natures could lead to bias, since it combines services assessed based on data that have different levels of availability.

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

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

Abiotic Services or Abiotic Indicators?

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

Conclusion

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

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

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

Despite the revised ES cascade model including human interventions in the supply of ES, further improvements should not only focus on a clear-cut distinction of human inputs as ES co-producers and managers but also demanders.

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

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

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Data Availability The authors declare that the data supporting the findings of this study are available within the paper, its supplementary information files and the hyperlinks detailed in the data tables.

Declarations

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

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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