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Landform and landscape mapping, French Guiana (South America)

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In this paper two geomorphologic maps (landform level and landscape level) are presented covering the French Guianan rainforest (84,000 km^2) using full-resolution Shuttle Radar Topography Mission (SRTM) data. The entire country was segmented into 224,000 landform units on the basis of an original object-oriented approach using a modified counting box algorithm. A Principal Components Analysis (PCA) followed by k-means clustering (Ward's method) identified 12 different landform types corresponding to theoretical elementary landforms. The landscape map was generated by analyzing the spatial distribution of the different landform types. The different maps and models were compared with topographic field data collected on 92 transects totaling 260 km in length. The object-focused approach is a very efficient method that preserves geomorphologic consistency and discriminates between landforms using simple descriptors that are easily understood by non-geomorphologists. Despite major noise in the data, the landform map proved to be reliable and provided a strong spatial structure for the definition of landscape units. We recommend using the landform map at scales 1: 100,000–1: 250,000. Landscape map, used on a 1:1,000,000–1:2,000,000 scale, enabled us to draw bio-geographical limits in this region and provides exhaustive relief information that usefully supplements the geological map.

Keywords: geomorphology; geodiversity; rainforest; remote-sensing; SRTM; Guiana shield

1. Introduction

Geodiversity, defined by Gray (2004) as 'the natural range of geological, geomorphological and soil features, (. . .) including their assemblages, relationships, properties, interpretations and systems' is one of the key components that explain biodiversity at different scales in both temperate and tropical areas (Nichols, Killingbeck, & August, 1998; Parks & Mulligan, 2010). Geomorphodiversity, which is part of this geodiversity, and was defined by Panizza (2009) as 'the critical and specific assessment of the geomorphological features of a territory' can therefore be used as a biodiversity indicator for the management of natural areas or for regional planning, in addition to geological data. Geomorphology remains underused in tropical countries, mainly because geomorphologic maps are difficult to produce at a regional scale due to the extended forest cover, insufficiently accurate geological and topographical data, cloud cover on satellite images, and poor field accessibility for data collection

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and validation. This is particularly true in vast forest areas that consist of gently undulating relief such as the Guiana shield and the Amazon and Congo basins where local and continental geomorphologic information is lacking (Sombroek, 2000).

At the request of the French Guiana public forest manager (ONF: Office National des Forêts) we produced two geomorphologic maps covering the entire country (84,000 km^2) using full-resolution Shuttle Radar Topography Mission (SRTM 1 arc sec ~ 30 m) data (see Main Map). The first, a landform map, considers relief forms at the mesoscale using the Dikau taxonomical hierarchy (Dikau, 1990), i.e. *mesoforms* of about 10^6 m^2. The second, a landscape map, considers relief-form associations at the macrorelief scale in the same taxonomy, i.e *macroforms* of about 10^9 m^2. The purpose of generating these maps is to evaluate the geodiversity of natural areas that are potentially threatened by mining activities and require protection by law.

2. Study area

French Guiana is located in the eastern Guiana Shield between the Oiapoque and Maroni rivers. The soils on this ancient, heavily eroded Precambrian shield (more than 1.9 Gyr old) are highly evolved, thick and chemically poor (Ferry, Freycon, & Paget, 2004). They have developed on volcanic, plutonic and metamorphic materials of the Paleoproterozoic age that are spatially organized in successive belts parallel to the Atlantic coast and to the rear of younger coastal sedimentary formations (Delor et al., 2003). The country's relief may be described as fairly flat, rarely exceeding 200 m, slightly tilted to the north-east, and dissected by an extremely dense network of rivers (Filleron, Le Fol, & Freycon, 2004). This monotonous area nevertheless features some isolated hills and inselbergs, with both tabular and linear relief. Most of these feature in three mountain chains that are parallel to the coast and frame three planer areas (see Paget, 1999 in Figure 3): (I) in the southern Tumuc Humac massif, inselbergs such as Mitaraka Mount reach an altitude of more than 650 m – detailed accounts of the geomorphology and geology of rock outcrops in this area are provided by Hurault (1963); (II) in the southern peneplain, rivers flow from the south through typical 'demi-orange' relief (Gruau, Martin, Leveque, Capdevilla, & Marot, 1985; Teixeira, Taasinari, Cordani, & Kawashita, 1989); (III) the Inini-Camopi Massif corresponds to the highest (up to 830 m) and is associated with river network deflexion to the east and west; (IV) the Central Massif (also called the central peneplain) runs from north of the fourth parallel to the Northern chain (V) and is associated with volcano-sedimentary rock often covered by lateritic duricrust that protect the highest relief of about 500 m (Choubert, 1957); and finally (VI), the coastal area which is a 15- to 20-km strip of lowland characterized by enlarged flat wetlands between lowered multiconvex reliefs. Inland areas are covered by almost continuous tropical rainforest that is one of the last of its kind to be almost undisturbed by recent human activity (Hammond, 2005). Natural habitats show slight variability and high species diversity, including 1600 tree species according to most recent estimates (Molino et al., 2009). The tree community is consequently complex, often with more than 150–200 species per hectare (Sabatier et al., 1997).

Previous studies of the geomorphology of French Guiana mainly considered the local scale (Filleron et al., 2004; Paget, 1999). The only regional study (Boyé, Brasseur, Réaud, Cabaussel, & Menault, 1979) was based on an expert approach and the corresponding report does not provide any methodological details on the geomorphologic classification employed.

3. Material and methods

3.1. *Landform mapping*

The landform map was computed from full-resolution SRTM data produced by NASA (Farr et al., 2007). As forest canopy height shows only small natural variations compared to the vertical accuracy of the data (Bourgine & Baghdadi, 2005), we used this derived digital elevation model (DEM) as a digital terrain model (DTM).

The entire country was segmented into 224,000 landform units using a novel object-focused approach based upon a modified counting box algorithm. The landform is the central object in our geomorphologic characterization and is defined as an interfluve bounded by relatively low-lying areas (thalwegs, passes and saddles) and organized around a more or less salient ridge-line. These high and low structuring lines are identified by computing local fractal dimensions (Shen, Zhou, Li, Shen, & Yang, 2001). By applying an appropriate multiplication factor to the DEM, this method tends to represent a theoretical convex relief as linear patterns in a cube-liked window, corresponding to a fractal dimension of less than 2, whereas theoretical concave relief tends toward a fractal value of 3 (Taud & Parraut, 2005). A threshold value is then calibrated to delineate landform unit boundaries. This calibration is based on previous manual segmentation (2007–2008) for purposes of a forest management plan. This huge training area (27,135 km^2) enabled us to calibrate the multiplication factor (100) and the fractal value threshold (2.75) using a map-curve test (Hargrove et al., 2006), a ROC-curve test (Sing, Sander, Beerenwinkel, & Lengauer, 2005) and a visual comparison. Seventeen topographic descriptors are computed for each landform unit. These include classical descriptors such as size, elevation [minimum, maximum, range], slope [mean and standard deviation] and a wetness index [hydromorphic area rate], but also novel descriptors describing landform per percentile slices and detailing shape complexity [gravilus coefficient for highest and lowest slices], vertical shape [elevation between different slices], flattening [ratio of flat area (slope $<$ 5%) for highest slice], plan shape [area ratio between different slices]. A Principal Components Analysis (PCA) was performed on the landforms and PCA scores were subjected to k-means clustering (Ward's method) to identify 12 different landform types corresponding to the theoretical elementary landforms.

3.2. *Landscape mapping*

The landscape map was generated by analyzing the spatial distribution of the different landform types. This analysis was conducted in five steps. First, the territory was manually segmented by an expert, based on the landforms' spatial distribution, i.e. boundaries were drawn around regions considered to be homogenous based on repeated patterns or dominant types, and thus defining relief units, also called regions. In a second step, 3 local indices were computed from the landforms map on 1.5 $\times$ 1.5 km sliding windows: (i) the Shannon-Weaver index indicating local diversity of the landform types; (ii) the contagion index indicating the aggregation level of the landform types (McGarigal, Cushman, Neel, & Ene, 2002); and (iii) the majority index indicating the local dominant landform type (O'Neill et al., 1988). Thirdly, each boundary in the manual segmentation was compared with spatial distributions of the 3 indices for validation. If an inconsistency was noted, the regions' segmentation was canceled or modified in accordance with the spatial variability of the indices. Then, another Principal Components Analysis was performed with 14 variables computed for each region (average Shannon-Weaver index, average contagion index and relative proportions of the 12 different types). Based on these results, a Hierarchical Cluster Analysis was used to assign a natural landscape type to each unit. Finally, permutation tests were used to compare landform type frequencies in the different landscapes with a neutral hypothesis and considering the relative proportions of all types in order to highlight significant relations between landscape categories and landform types.

The entire process has been summarized in a work chart (Figure 1) and an extract of the resulting landforms map is shown (Figure 2 and Main Map).

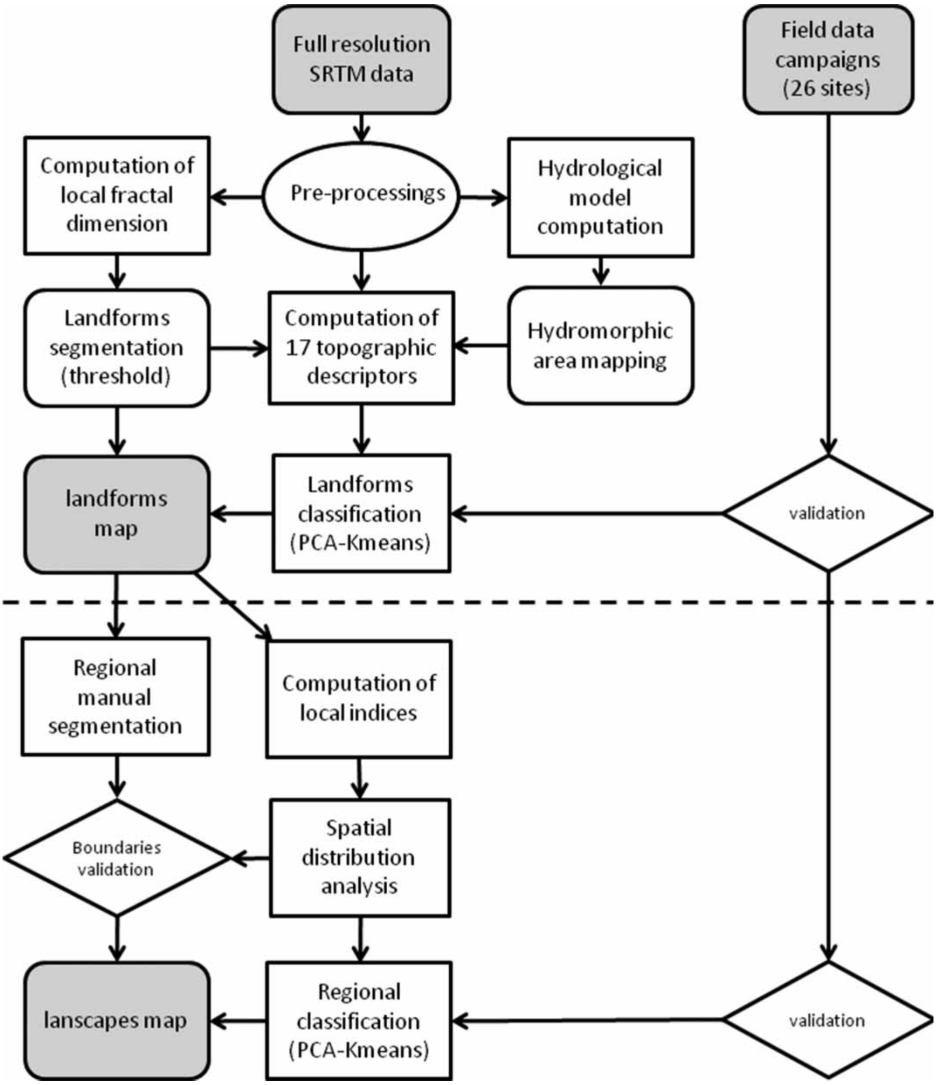

Figure 1. Work chart.

3.3. *Validation*

The different maps and models were compared with topographic field data collected on 92 transects totaling 260 km in length. These data, including natural habitat descriptions, topographic profiles, and soil types, were collected at 24 sites across French Guiana and thus reflect its geographic and ecological variability (Figure 3). Habitat descriptions were used to validate the hydromorphy index. Slope, elevation and topographic position occurrence measured on the transects were used to interpret landforms and landscape classes. A Garmin global positioning system receiver (60CSX) was used to geolocate the data. Slope angles and distances were measured using a Vertex laser rangefinder.

4. The geomorphologic map

The object-focused approach is a very efficient method that preserves geomorphologic consistency and discriminates between landforms using simple descriptors that are easily understandable

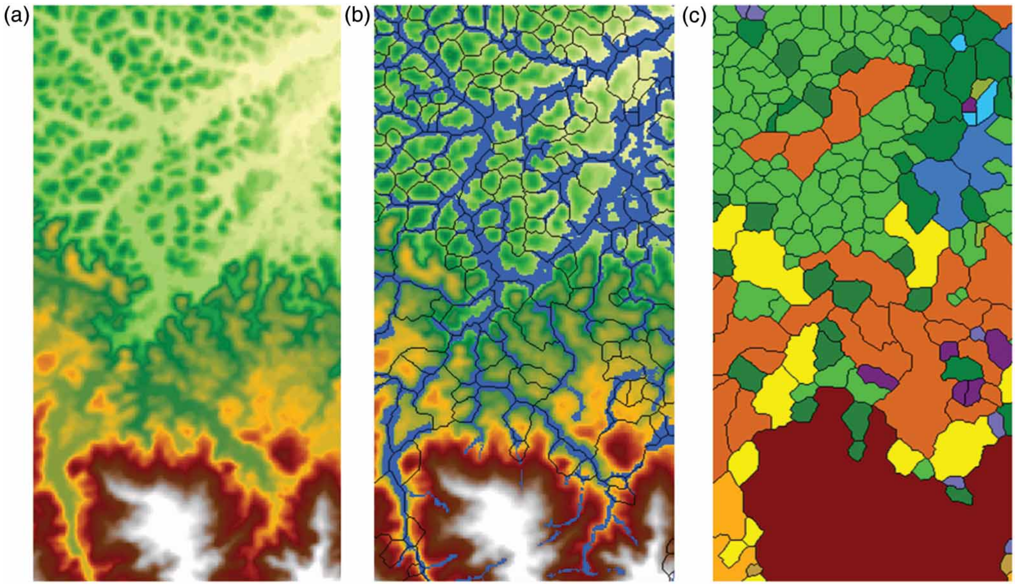

Figure 2. The three steps in landform mapping (current map).

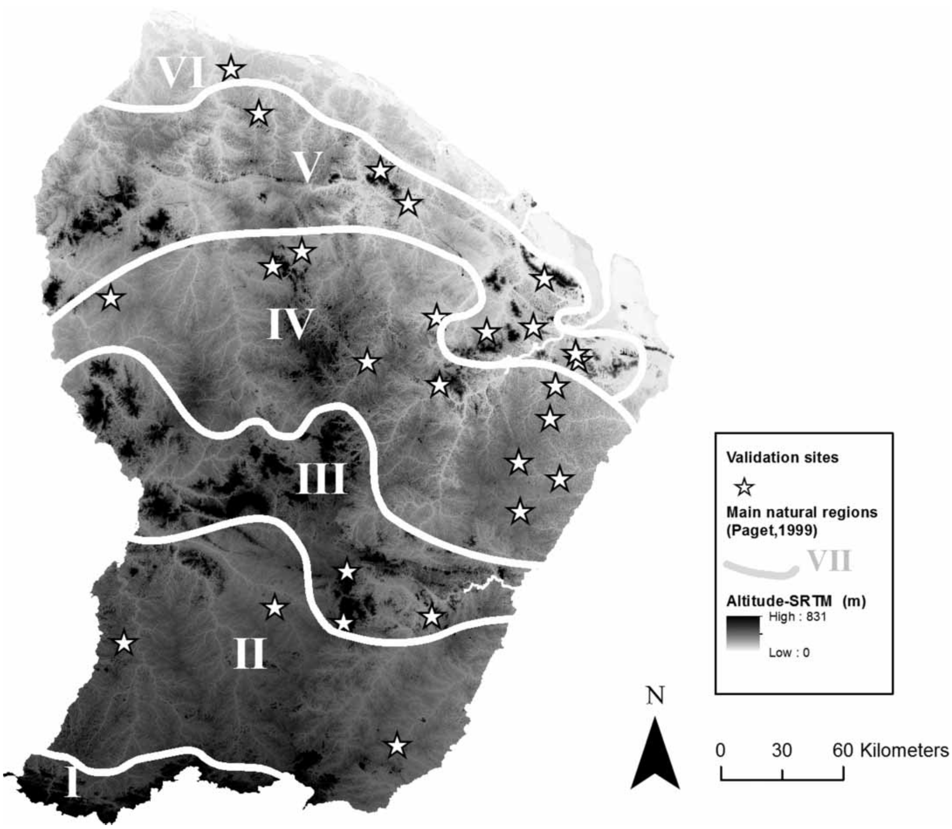

Figure 3. Field-site location and main geographic regions from Paget (1999).

Table 1. Landform type main descriptors (mean ± standard deviation) and interpretation.

Type	Size (km^2)	Altitude range (m)	Altitude base (m)	Hillside slope (%)	Uphill flattening (% area)	Hydromorphic Index (% area)	Number of landforms	Description of type
1	**>0.5**	40–60	60–150	10–15	**10–30**	<40	23 819	Large-size flattened relief
3	**<0.5**	**<20**	0–100	0	**60–100**	**50–100**	5 777	Small-size and flat wetland (very similar to 11)
4	**<0.5**	40–60	0–100	**15–22**	**<10**	<40	33 223	Small-size rounded hill
5	**<0.5**	40–60	100–200	**12–20**	**10–30**	<40	35 330	Small-size flattened hill
6	<0.5	**20–35**	90–170	**7–15**	15–45	20–50	18 587	Lowered half-orange
7	**>1**	**100–150**	70–200	>20	<10	<40	6 458	Large-size and high hill
8	**>2**	**>150**	70–200	>20	<10	<40	1 101	Very large and high hill to mountain
9	<0.5	**25–40**	40–100	**10–15**	10–20	20–50	36 195	Half-orange (typical)
11	**<0.5**	**<20**	0–100	0	60–100	**50–100**	2 946	Small-size and flat wetland (very similar to 3)
12	<0.5	**20–30**	0–100	5–9	20–60	40–80	14 078	Wet hillock (low base-level)
13	<0.5	**20–30**	100–200	7–12	20–60	20–60	18 673	Wet hillock (high base-level)
14	**>0.5**	10–40	0–100	0–5	**60–100**	**50–100**	4 424	Large-size flattened and wet relief
15	**>0.5**	60–90	60–150	**15–25**	**<10**	<40	23 705	Large-size and rounded hill

by non-geomorphologists: horizontal and vertical dimensions (size and range), landform position relative to the regional base level (base altitude), vertical profile (mean hillside slope and uphill flattening) and drainage density (hydromorphic rate).

The main descriptors used for landform interpretation are given in Table 1 and Figure 4.

Despite substantial noise in the data due to the small size of the landform units, discretization of variables in percentiles and relatively poor accuracy of the DEM, the landforms map obtained is consistent with previous expert-based descriptions (Boyé et al., 1979; Choubert, 1957). Its strong spatial structure (Moran index: z-score 123.47 – p-value <0.001) provided a solid basis for the definition of landscape units (called regions).

The landform type distribution analysis resulted in the identification of 82 regions. The Hierarchical Cluster Analysis then classified these into 12 landscape types that were subsequently grouped into five main categories based on Migon (2009) typology as they predominantly developed on crystalline rock: plain landscapes (AA, AB, AC); typical multi-convex landscapes (B, I, J); multi-concave and joint-valley landscapes (C,D); more or less dissected plateaus (E,F,G) and all-slopes topography (H).

Landform types 7 and 8, which were spatially correlated and frequently associated with type 15, corresponded to the highest relief (>100 m) and fit with landscape type H. These 'small mountains', found on ultra-basic to alkaline vulcanite in the northern part of French Guiana, are usually capped by lateritic soils on their summits, protecting them from erosion. They also include the highest chain of inselbergs that runs toward the southern boundary and prolongs the backbone of the Tumuc-Humac region. Table 2

Very flat landforms (types 11, 14, 3 and 12) are mostly found in the coastal region and along the main rivers. They include large marshy or swampy areas, and seasonal-flood terraces. They fit with the old coastal plain landscapes (type AA, AB, AC).

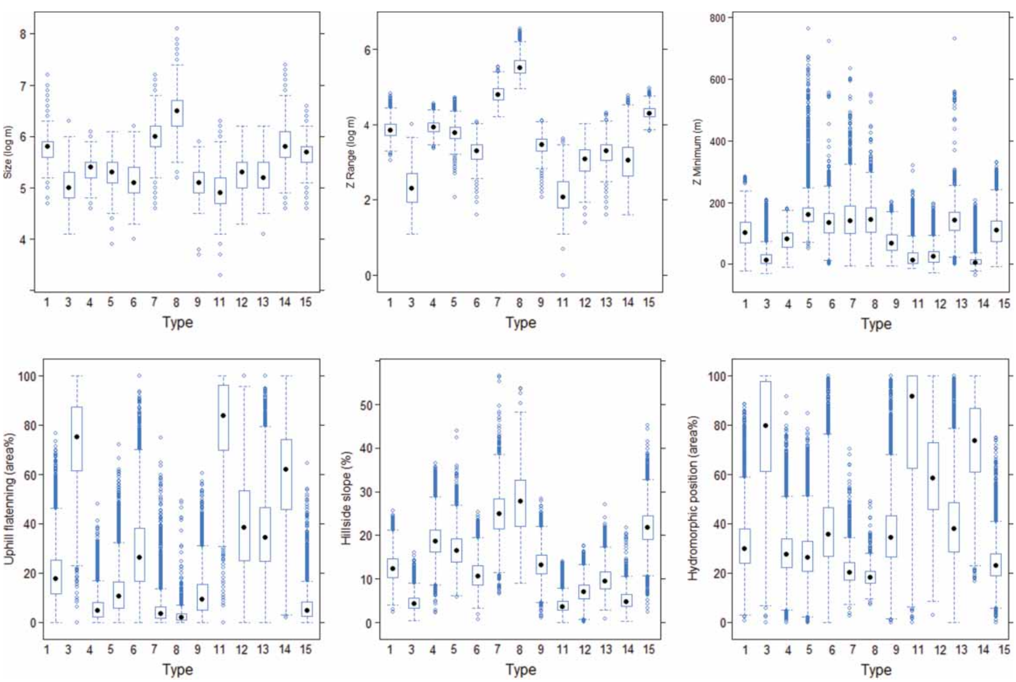

Figure 4. Box-plot of the six main landform descriptors (mean $\pm$ standard deviation): size, altitude range, altitude minimum, uphill flattening, hillside slope, hydromorphic area rate.

Table 2. Landscape descriptions and significant relations with landform type (bipartite permutation-test: $++\ p > 0.99$, $+\ p > 0.95$, $-\ p < 0.01$, $p < 0.05$) in gray the closest relation (resulting from Discriminant Analysis).

Code	Landscapes short description	Landscape type based on Migon typology (2006)	Significant association with landform types												
			14	3	11	12	9	4	1	13	6	5	15	7	8
AC	Coastal flat plain	Plain	++	++	++	++	−−	−−	−−	−−	−−	−−	−−	−−	−−
AA	Coastal plain with low reliefs	Plain with residual hills	++	++	++	++	−−	−−	−−	−−	−−	−−	−−	−−	−−
AB	Plain with residual reliefs (back-coastal)	Plain with residual hills	++	++	++	++	++	−−		−−	−−	−−	−−	−−	−−
C	Low hilly area and large valley	(Low) joint-valley landscape	−−	++		++	++	++	++	−−	−	−−	−−	−−	−−
B	Complex hilly area	Hilly multiconve × landscape		++	+	++	++	++	++	−−	−	−−	++	++	−−
J	Regular pattern hilly area	Hilly multiconve × landscape	−−	−−	−−	−−	++	++	++	−−	++	−−	++	−−	−−
I	Peneplain with moderate hill	Hilly multiconve × landscape	−−	−−	−−	++	++	++	++	++	++	−−	−−	−−	−−
D	Inland plain	(Close) multiconcav landscape	−−	−	++	−−	−−	++	++	++	++	++	−−	−−	−−
E	Moderate plateau with inselberg	Plateau	−−	−−	−−	−−	−−		++	++	++	++	++	−−	−−
F	Hilly plateau with inselberg	(Dissected) plateau	−−	−−	−−	−−	−−	−−	++	+	++	++	++	++	−−
G	High dissected plateau	Dissected plateau	−−	−−	−−	−−	++	++	−−	−−	−−	++	++	++	−−
H	High hill and 'mountain'	All-slopes topography	−−	−−	−−	−−	−−	++	−−	++	++	++	++	++	++

Landform type 13, which is slightly undulating, was found to be located inland, especially in the 'Waki' basin, a major network of rivers surrounded by very high relief. It forms a novel region (type D) corresponding to a rare, multi-concave landscape that has not been described in the past in French Guiana, and which could indicate the presence of a large eluvial system (i.e. residual deposit after fine weathering products have been washed away).

Landform types 1 and 15 are fairly common and appear to correspond with large and complex forms similar to plateaus and large hills, whereas types 4, 5, 6 and 9 are associated with simple and smaller forms similar to the typical half-orange and resembling a hill shape. Regarding the relative proportions of these types, different landscape types were distinguished in Guiana's large central massif: (a) more or less elevated and dissected plateaus [E, F, G] in the eastern and southern part – (b) smaller and very dissected multi-convex landscapes [B, I, J] in the western and northern part – (c) and occasionally joint-valley landscapes [C] corresponding to an intermediate form in contact with the coastal plain. Spatial and temporal variability in weathering dynamics appears to be a key factor in explaining this landform grading (Thomas, 2006), but this hypothesis needs validation.

5. Conclusions

Thanks to their special design, these two maps are understandable on different scales by non-geomorphologist users, particularly foresters, managers, and other planning stakeholders who need simple indicators in their efforts to take account of geodiversity. These GIS data can also be used as an efficient explanatory factor in ecological research, as demonstrated in a companion study using floristic and faunal data collected on the same field transects (Richard-Hansen et al., 2010).

Given the noise in the original data (that represent the canopy, not the ground), and given the additional noise introduced in the various stages of the analysis, we recommend using these landform maps at scales in excess of 1: 100,000–1: 250,000, not for local studies (i.e. at scales of 1: 50,000 or less). The landscape map based on the landforms analysis should be used on a 1:1,000,000–1:2,000,000 scale. This has enabled us to draw biogeographic limits in this region and provide exhaustive relief information that usefully supplements the geological map. These new data are of considerable value in evaluating the efficiency of the current network of protected areas in French Guiana, and may also serve to guide ongoing ecological surveys (ZNIEFF inventories).

Software

Landforms were computed using Esri ArcGIS. The landscape analysis was performed using Fragstat v2 (McGarigal et al., 2002) and all statistical analyses were performed using R1.9 (http://www.r-project.org/).

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