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RESEARCH ARTICLE

Land surface diversity: a geomorphodiversity index of Italy

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Abstract

Geomorphodiversity refers to the variety of landforms and morphological processes characterizing the landscape. The definition of an index to quantify geomorphodiversity is a relevant step for multiple fields of Earth sciences, since it is widely accepted that the variability of the geosphere deeply influences the diversity of the biosphere. Such an index should describe the number and type of landforms and geomorphological processes. We propose a quantitative land surface diversity index valid for Italy, considering multiple input quantities to describe geological constraints and geomorphological processes. Critical issues were the selection of moving window size for focal statistics operations, to calculate local diversity of slope, lithology, drainage density and terrain forms in individual raster maps. We compared the index with traditional geomorphological maps, in selected locations, in which information was available. Results show that a minimal set of heterogeneous data is a satisfactory approach to investigate the landscape diversity. Relating processing parameters and terrain spatial characteristics to the dataset resolution is a good choice to assess a reproducible land surface diversity index. Inclusion of drainage density allows the improvement of results in flat areas, in which other factors show trivial results. We argue that the index is relevant for land use management, assessment of ecodiversity, and it may help describing the interaction between abiotic and biotic compartments.

KEYWORDS
Geomorphodiversity, Geodiversity, GIS, Terrain classification, Spatial analysis, Digital elevation model

1 | INTRODUCTION

Geodiversity represents the natural range, or diversity, of geological (rocks, minerals, fossils) geomorphological (landforms, topography, physical processes), and soil features Gray (2013). Compared to the topographic heterogeneity, it represents a more complete characterization of the Earth surface diversity Guzzetti and Reichenbach (1994), Minár and Evans (2008), Tukiainen et al. (2017). Components of geodiversity stem from several Earth compartments, ranging in climate, topography, geology and hydrology, especially if considered for their potential of providing resources for biological complexity Parks and Mulligan (2010).

Different attempts exist in the literature of a formal and objective definition of geodiversity, in the last few decades Gray (2008 2013 2021). They fall within two main groups. Qualitative analyses focus on specific land units, themes, regions and environments Gordon and Barron (2013), Mansini Maia and de Alencar Castro (2015), Migoń (2021), de Paula Silva et al. (2021). Quantitative and objective methods exist to assess in particular the geomorphological variability of a landscape, which is the result of the interaction between geological complexes, surface processes and climate action Benito-Calvo et al. (2009), Zarnetske et al. (2019), Gonçalves et al. (2020), Manosso et al. (2021). Landforms are representative of geomorphodiversity, as they are the result of the interaction between the lithological types, the surface processes and the climatic variables.

Examples exist of alternative methods, combining qualitative and quantitative approaches Jankowski et al. (2020), Najwer et al. (2022); a comprehensive review is in Zwoliński et al. (2018). Nevertheless, no general agreement subsists on a single method yet Crisp et al. (2021). Considering only the geomorphological component, the geomorphodiversity parameter could be defined Panizza (2009). Melelli et al. (2017) proposed a quantitative index for assessing a geomorphodiversity index (GmI) within a GIS–based approach. The method considered the spatial variability of geological, morphological and hydrographic parameters, and combined them into a single raster index.

Abbreviations: GmI, geomorphodiversity index; DEM, digital elevation model; GIS, geographic information system.

The GIS approach largely relies on the analysis of a digital elevation model (DEM), derived attributes by morphometric analysis, and their relationship with geological data. An index based on a DEM has the advantage of being highly reproducible on wide areas, and the potential of application at different scales and resolutions.

Here, we expand on the approach of Melelli et al. (2017), introducing (i) an advanced method to single out different terrain forms Jasiewicz and Stepinski (2013), (ii) a lithological map recently developed at 1:100,000 scale Bucci et al. (2022), and (iii) extending the approach to the whole of Italy.

Challenges faced during the analysis were the need of (i) selecting specific values for numerical parameters involved in the process, as window size for focal statistics (ii) obtaining an index that equally represents diversity of areas with large topographic variability and flat areas, and (iii) comparing the index at national scale, with relevant maps. Throughout this work, we aimed at an objective and reproducible procedure – either in selection of numerical parameters, calculation of the land surface index, and in the comparison with existing maps.

The index proposed for Italy in this work is relevant for several applications, including local land use planning, environmental management and geoheritage conservation Reynard and Brihla (2018), Schrodt et al. (2019), da Silva et al. (2019), de Paula Silva et al. (2021). The most promising applications of GmI concern the relationship between geodiversity and biodiversity. For example, Whittaker et al. (2005) introduced the idea of "Conservation Biogeography", and Parks and Mulligan (2010) discussed their spatial and temporal variations. The issue is particularly relevant in urban areas Del Monte et al. (2016), Ilić et al. (2016), Reynard et al. (2017), whose expansion causes loss of geodiversity Santos et al. (2017).

2 | THE STUDY AREA

The Italian peninsula covers an area of around 300,000 km^2 from the 35°29′26″ to the 47°05′29″ latitude N, from 6°37′32″ E longitude toward West and to 18°31′13″ E longitude to the Eastward.

From a geological point of view, the Italian territory can be divided in different units corresponding to physiographic properties. The norther part of Italy is the continental one, where the northward arc of the Alpine chain shows the highest altitude of the country (Mont Blanc, 4,810.90 m a.s.l.) and divides this area from the Italian peninsula (Central and Southern Italy). In the Alpine, Austroalpine and subalpine units the crystalline massifs prevail with eruptive and metamorphic rocks.

The central and southern part of the Italian territory is peninsular, where the Apennines Mountain chain (maximum altitude in the Gran Sasso Mountain, 2,912 m) is the most evident feature of the physical landscape. This area corresponds to the Apennine Unit where flyschoid and calcareous sequences are present.

Italy has a substantial insular portion. Sardinia and Sicily are the largest islands, and minor islands are in numerous archipelagos. While Sicily is in continuity with the Apennine Unit, Sardinia Island is part of Sardinian–Corsican block with crystalline massifs.

The Alps and Apennines chains are the most relevant mountain areas (overall the 35.2 % of the territory). The hilly zones mark the 41.6 % of the total area (max altitude 800 m a.s.l.), in the central and southern part of the Country and in the pre–alpine range. The remaining 23.2 % of the Country is flat; only with the Po Valley is the two thirds of the flat areas, followed by the Tavoliere delle Puglie in the South Apulia, the Campidano area in Sardinia or the Maremma in Tuscany. These gentle or flat areas are included in the post–orogenetic series with continental and marine deposits sedimented in the post–orogenetic phases.

Italy is characterized by a heterogeneous distribution of climate, ranging from the Mediterranean warm–dry to the Alpine cold–humid climate Chelli et al. (2017), physiography, vegetation cover and land use Smiraglia et al. (2013).

Moreover, Italy is one of the most geodynamically active areas on Earth, with a high seismicity in several areas, and it is the first European Country for number and magnitude of seismic events, with a maximum higher than 7.0 Mw and a return period of 20–25 years, but with numerous events with Mw 5–6 every 3–4 years. The endogenous activity is confirmed by the presence of several volcanoes (Mt. Etna, Sicily, 3,295 m is the highest active volcano in Europe), and it is the cause for the exogenous activity, which defines, together with the different climate conditions, the variety and the attractiveness of the Italian landscape.

3 | MATERIALS

For the assessment of a proxy of geomorphological variability, we chose a few input datasets (Fig. 1): Section 3.1, a DEM with a horizontal resolution of 25 m x 25 m, for the assessment of topographic attributes, as the slope angle, for deriving terrain forms and for corresponding drainage network; Section (3.2), a map of the geological complexes in a polygon vector format; Section 3.3, a homogeneous terrain subdivision in topographic units for the whole of Italy based on its terrain characteristics; Section 3.4, a comprehensive dataset of landforms for an empirical comparison of the GmI map.

A detailed description of all the input dataset is in the following paragraphs.

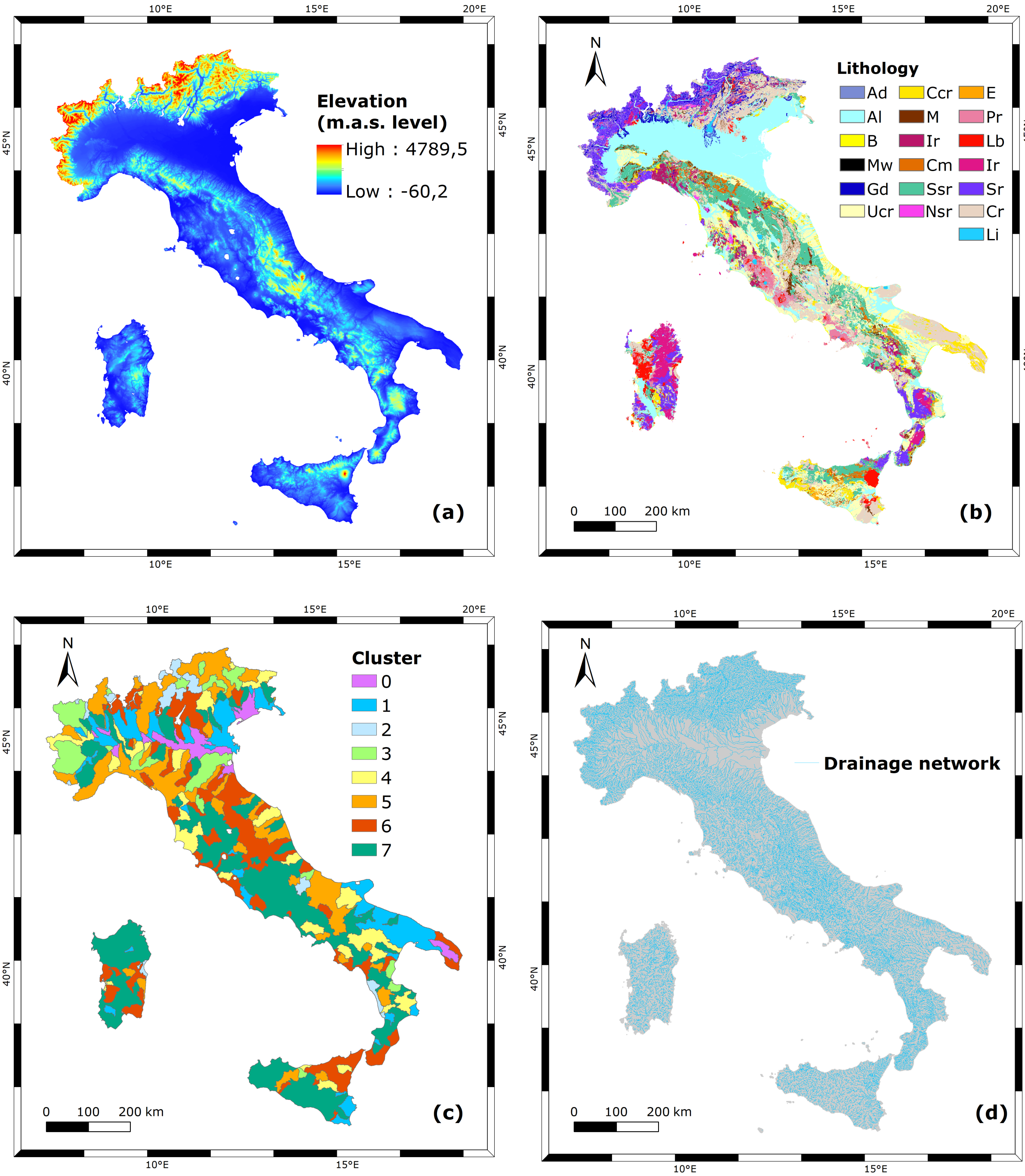

FIGURE 1 Input datasets: (a) EU–DEM (25 m resolution), (b) geological map by Bucci et al. (2022), and (c) terrain classification in geomorphological clusters by Alvioli et al. (2020). Panel (d) shows the drainage network obtained from the EU–DEM in (a).

3.1 | Digital elevation model

The "EU–DEM" (Fig. 1a) is a raster layer supplied by the European Environmental Agency (EEA), which is a full, open and free access dataset (https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem). EU–DEM is a hybrid product based on SRTM and ASTER GDEM. The horizontal resolution is 25 m and the vertical accuracy is of 2.9 m, a good compromise considering the study area extent and the accuracy required for a spatial index. EU–DEM covers the entire Europe, which in principle allows comparing different study cases on a wide area. We downloaded from the same source a drainage network in polyline vector format.

3.2 | Geological vector data (Li)

The composition of the main bedrock and its lithological characteristics deeply influences the exogenous landscape processes, the topographic arrangement, the geomorphological features and the resulting water flow paths. Lithological variability is an important parameter as a triggering parameter for the variability of soil type and so the evolution of biodiversity, which is correlated to the abiotic complexity Erikstad (2013), Pellitero et al. (2011), Chakraborty and Gray (2020).

Recently, Bucci et al. (2022) proposed a digital geological layer of Italy (Fig. 1b). The authors used a similar approach to previous elaborations of geological data Hartmann and Moosdorf (2012), Donnini et al. (2020), though at much higher resolution. The open access map, available in vector format at the scale 1:100,000, was obtained from the classification of a digital database. The map was mainly designed for geomechanical modeling Alvioli et al. (2021 2023), geomorphological analysis, terrain classification Alvioli et al. (2020), and other purposes. In the map, geological formation are grouped in 19 lithological classes (Table 1) summarized as follows: about 82 % of sedimentary, 9 % metamorphic, 4 % plutonic, and 5 % volcanic rocks. The high resolution of this national map highlights the relationship between lithology and surface processes, taking into account multiple geomorphological, geo–hydrological and environmental issues Bucci et al. (2022), and it is relevant for the definition of a GmI.

TABLE 1 Lithological classification by Bucci et al. (2022). Figure 1b shows the geographical distribution of the classes.

ID	Lithological class	Abbreviation
L1	Anthropogenic deposits	Ad
L2	Alluvial deposits	Al
L3	Beaches and coastal deposits	B
L4	Mass wasting material	Mw
L5	Glacial drift	Gd
L6	Unconsolidated clastic rock	Ucr
L7	Consolidated clastic rocks	Ccr
L8	Marlstone	M
L9	Mixed sedimentary rocks	SM
L10	Chaotic –- mélange	Cm
L11	Siliciclastic sedimentary rocks	Ssr
L12	Carbonate rocks	Cr
L13	Evaporite	E
L14	Pyroclastic rocks	Pr
L15	Lavas and basalts	Lb
L16	Intrusive rocks	Ir
L17	Schistose metamorphic rocks	Sr
L18	Non–schistose metamorphic rocks	Nsr
L19	Lakes and Ice	Li

3.3 | Subdivision in topographic units

We considered the classification of Alvioli et al. (2020), who used unsupervised clustering of Italy into seven topographic classes (Fig. 1c). The classification resulted from analysis of 439 hydrological basins, with average area 741 km^2, from a topographic point of view. Specifically, the analysis considered the distribution of size and average aspect of slope units contained in each of the basins. Slope units are a geomorphological homogeneous terrain subdivision, mostly used in landslide studies Alvioli et al. (2016). Each of the basins considered in the study contained a large number of such units, which have an average area between 0.5 and 1 km^2, in different geographical regions. Slope units are undefined in flat areas; thus, the classification into clusters only considers regions with non–negligible slope.

From a topographic and lithological point of view, the clusters 1 and 7 of Fig. 1c match the flattest areas of Italy, with few steep terrains and a high prevalence of clastic and carbonate rocks. Clusters 2, 3 and 5, mostly on the mountainous areas, have a different setting: they show a strong abundance of steep and very steep terrains and a predominance of metamorphic rocks, carbonate rocks, unconsolidated clastic lithotypes and turbidite. The clusters 4 and 6 are the intermediate topographic setting and, in both cases, the most common rock type is sedimentary.

We effectively considered Italy divided into eight clusters: seven derived from the dataset the above–mentioned publication, and one additional cluster obtained by GIS raster difference, and containing flat areas (*cf.* Fig. 1c). This additional group (referred to as "cluster0") was essential to assess the GmI on the entire study area. Specifically, we used the eight clusters to constrain the size of moving windows (focal statistics) to calculate the variety of the input features considered here, described in Section 4.4. We used individual (much smaller) slope unit polygons, instead, to select the parameters for landform classification, described in Section 4.2.

3.4 | Cartography for empirical assessment of GmI

The use of digital geomorphological dataset supplied by the regional administrations represented a good option for comparing the GmI map with existing cartography. These datasets typically show the number and type of landforms in one specific area. In this work, for validation, we relied on the maps supplied by the following Italian administrative regions:

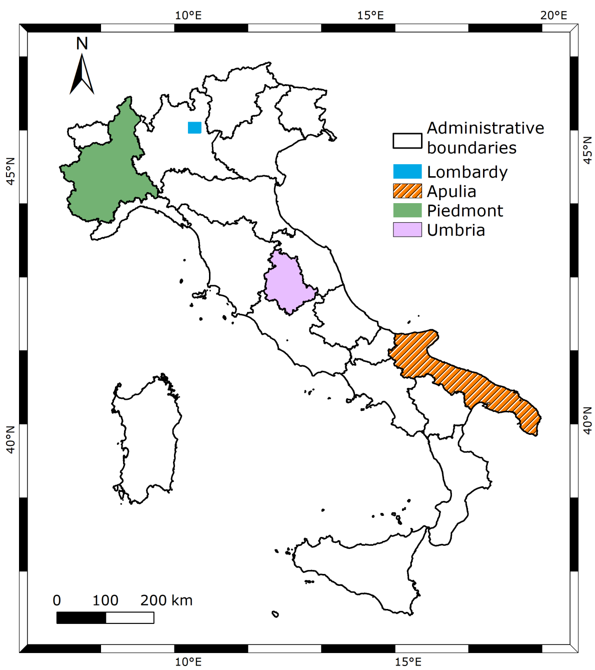

FIGURE 2 The areas considered for the empirical assessment of GmI, described in Section 3.4.

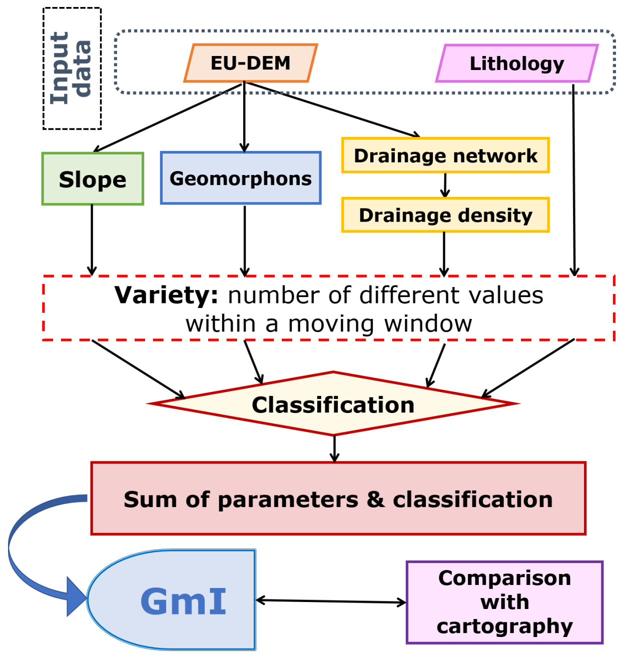

FIGURE 3 Flowchart describing the steps of the analysis. The input datasets are in Fig. 1; the variety assessment for each input and the result classification are described in Section 4 and shown in Fig. 4; the final assessment of GmI is described in Section 5 and shown in Figs. 5 and 6.

Piedmont (https://webgis.arpa.piemonte.it), Lombardy (https://sicurezza.servizirl.it), Umbria (https://dati.regione.umbria.it) and Apulia (https://pugliacon.regione.puglia.it). The selected areas cover different geographic and climatic parts of the Italian territory. We acknowledge that the four datasets are not homogeneous. In fact, each administration has a different methodology to build a geomorphological dataset, and, most importantly, in some cases they give free access only to small subsets, which makes the validation analysis trickier. Moreover, none of these datasets can be considered a complete geomorphological mapping of features and processes acting on the corresponding areas. Nevertheless, they were the only publicly available data, in areas of sufficiently large size and already available in a digital format. In particular, while Piedmont, Umbria and Apulia have a free geomorphological map for the whole of the region, in the area of Lombardy we tested only the available data covering a limited portion of the region called "Breno_78".

The multiple landscape features are represented through points, polylines or polygons, fully described in the related attribute table.

As an example, in the Piedmont database we mainly considered: rock glacier deposits, glaciers, terraced alluvial and debris flow deposits, lakes and block stream. In the Lombardy validation dataset we considered: *roche moutonnée*, glacial striae, springs, dolines, quarries/mines and caves. In the Umbria region, the dataset was divided in three vector shape files for point, lines and polygons, respectively, with: alluvial deposits, anthropic deposits, landslides, dumps, alluvial fans, fans due to fluvial processes and debris flows. In Apulia, the features were point shape files of caves, lame gravine, dolines, slopes, swallow hole and backshore dunes.

Figure 2 shows the geographical location of the four selected areas.

4 | METHODS

The preparation and the analysis of all the features were carried out in a GIS environment, using GRASS GIS (https://grass.osgeo.org/) and ArcGIS (©ESRI) tools.

Figure 3 shows a flowchart of the procedure. In the figure, we distinguished input data, intermediate processing steps (pre–analysis), and classification steps (analysis) to obtain the GmI map (output).

4.1 | Slope (Sl)

Slope is a topographic attribute that determines the effectiveness of processes that shape the Earth's surface through the action of water, gravity and ice. Erosion, transport and accumulation processes contribute to the modification and the denudation of the bedrock. Consequently, the assessment

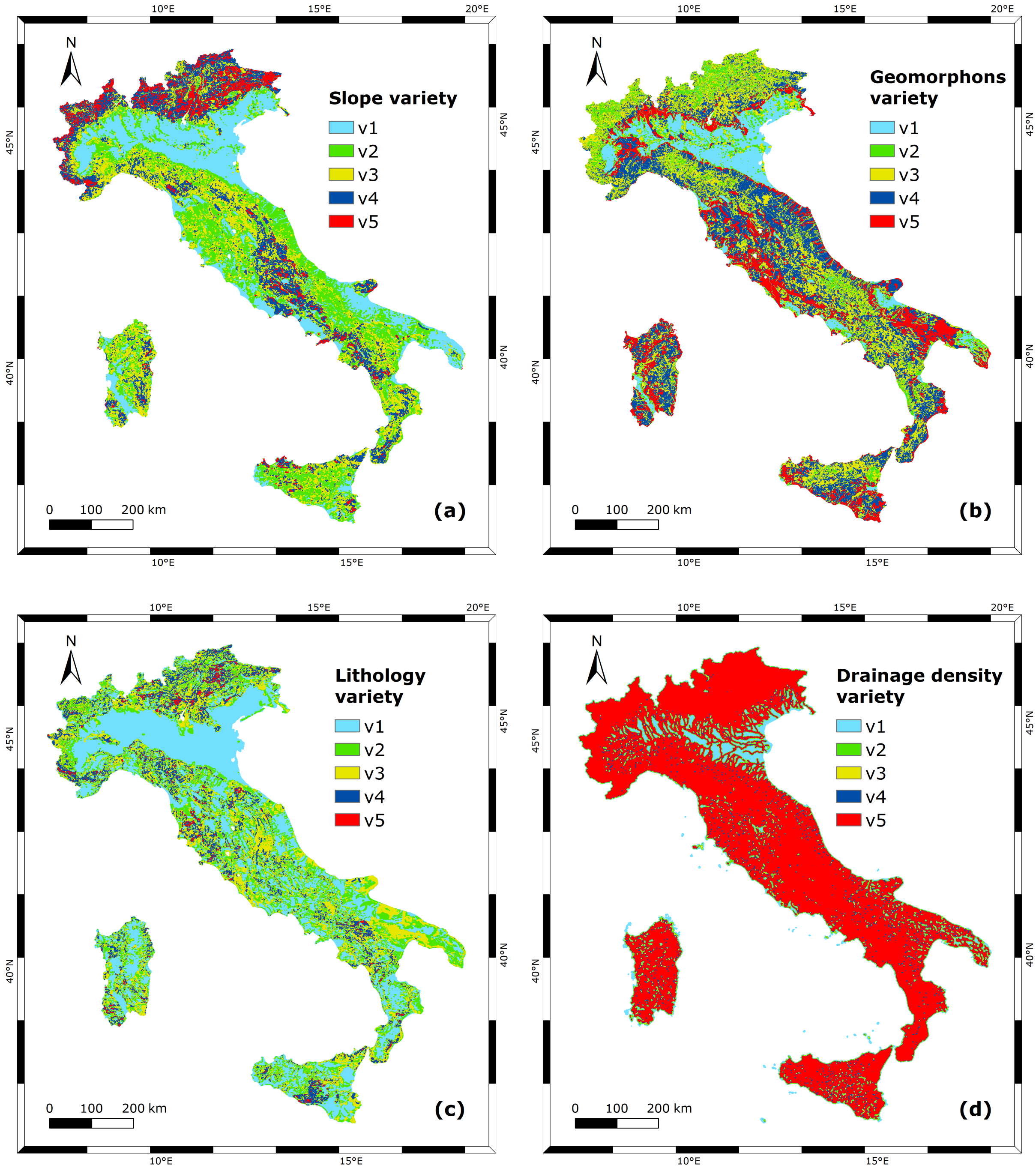

FIGURE 4 Variety of (a) slope, (b) landforms (geomorphons), (c) lithology, and (d) drainage density. All quantities obtained using moving windows (focal statistics) with sizes listed in Table 2.

of slope is deeply connected to the heterogeneity of lands, resulting into several physical shapes of an area.

The slope raster map was calculated from the EU–DEM, using the GRASS GIS tool `r.slope.aspect` Hofierka et al. (2009).

4.2 | Landforms (Gm)

The different morphological features existing are the result of the processes that shape the landscape. This makes landforms relevant to assessing the diversity of morphological features.

Thus, the number, areal extent and type of landforms were included between the input parameters.

Geomorphological maps are thematic data that identify the different landforms. Nevertheless, analysis of such thematic maps requires time and a high expertise of the operators and, more importantly, they are seldom available in a full coverage and open access. In addition, geomorphological maps may be very heterogeneous, depending on the scale, on subjectivity, and on the choice of symbology in the legend.

On a totally different account, in the last decades, the field of geomorphometry particularly focused on the study of automated or unsupervised classification of landforms, which can be suitable for a fast growth and analysis on larger areas Gioia et al. (2021). Methods of this type only require a DEM but, since the translation from continuous morphometric variables to their derivatives is subordinated to scale–dependence, many quantitative and automated approaches have been proposed Evans (2003), Drăguţ and Eisank (2011), Drăguţ et al. (2011), Liucci and Melelli (2017), Liucci et al. (2017), using secondary topographic attributes Wilson and Gallant (2000), Shary et al. (2005), the MRS method Baatz and Schape (2000), or using ALCoM statistical technique van Niekerk (2010). In geomorphometry the landscape profile has also been investigated though the topographic position index, first proposed by Weiss (2001), which compares the elevation of each cell in a DEM to the mean elevation of a specified neighbourhood around that cell Melelli et al. (2017).

TABLE 2 Moving window radius for the variety assessment within each cluster. Cluster 0 refers to flat areas, whereas the clusters from 1 to 7 refers to the subdivisions obtained by Alvioli et al. (2020) (*cf.* Fig. 1c).

Cluster ID	Average area [km^2]	Radius (no. of cells)
0	641	321
1	501	91
2	757	35
3	946	39
4	193	57
5	118	43
6	180	55
7	153	51

In this work, the classification of landform features, one of the inputs for GmI assessment, was delegated to the geomorphons model proposed by Jasiewicz and Stepinski (2013). The model is implemented in the GRASS GIS tool `r.geomorphon`, which uses a machine vision approach to automatically map land surface shapes. The model is strictly dependent on two main threshold values, called "search" and "skip". They define an inner and outer search radius surrounding the focus cell, in units of grid cells. The tool can select which landform fits the best the topography within the inner and outer search radii. The tool is easy to use, and can detect up to ten possible landform geometries, classified either as flat, summit, ridge, shoulder, spur, slope, hollow, footslope, valley and depression. As highlighted by Gioia et al. (2021) this tool uses "a computer vision approach" that self–adapts to the topographic characteristic of the area.

TABLE 3 Breaks considered for classification of diversity maps (*cf.* Section 4.4) in Fig. 4 and Fig. 5. Breaks were obtained for each map using the Jenk's natural breaks method. For slope, landforms and lithology they are different within each morphological cluster (see Fig. 1c).

	Cluster	Break values			
	ID	I	II	III	IV
Slope [deg]	0	5	8	13	24
	1	9	19	30	43
	2	23	37	48	58
	3	15	32	46	58
	4	14	27	40	54
	5	15	30	43	56
	6	15	29	41	54
	7	13	25	36	48
Landform class	0	1	3	5	7
	1	2	4	6	8
	2	3	5	6	7
	3	2	5	6	7
	4	2	4	6	7
	5	3	5	6	7
	6	2	4	6	7
	7	2	4	6	7
Lithology class	0	1	2	3	4
	1	1	2	4	6
	2	2	3	4	6
	3	1	3	4	6
	4	1	2	4	6
	5	2	3	4	6
	6	1	2	4	6
	7	2	3	4	6
Drainage density	–	5	12	20	26
GmI	–	7	10	13	15

To select numerical values of the "skip" and "search" parameters we considered the slope–unit map (see Section 4.2) and terrain classification into "clusters", prepared for the whole of Italy by Alvioli et al. (2020). Slope units are elementary units of landscape, and their shape and size are strongly dependent on morphogenetic processes, and reflect the spatial distribution of geomorphological features. Assuming that the size of landforms should be comparable to that of the slope unit in which they are contained, we considered the eight clusters shown in Fig. 1c and calculated the maximum distance within each

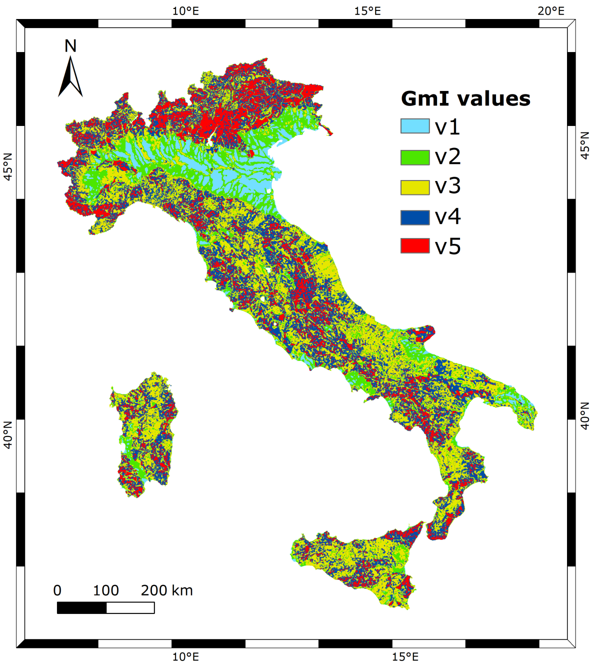

FIGURE 5 Geomorphodiversity Index (GmI) on the whole of Italy. The index values range from v1 (lowest diversity) to v5 (highest diversity).

slope unit polygon, in each cluster. We used this value, in each cluster, as the outer search radius ("search" parameter), and one–half of that as the inner search radius ("skip" parameter). This approach effectively sets the local scale of landforms in an objective and reproducible way.

4.3 | Drainage density (Dd)

In order to consider fluvial processes as a relevant morphological agent, in particular on flat areas, where topographic attributes are mostly uniform and mass wasting dependant processes less significant, we considered a drainage network. The issue of unrepresented topographic features is common to other settings: Manosso et al. (2021) found lower geodiversity on interfluves landforms and in areas with a homogeneous relief in Brazil, and Vörös et al. (2021) had similar issues dealing with volcanic features in France.

We downloaded the drainage network dataset, derived from EU–DEM, from the European Union's Earth observation programme Copernicus (https://www.copernicus.eu/en) (Fig. 1d). In principle, a drainage network can be extracted from a DEM in a GIS environment Tucker et al. (2001), Metz et al. (2011), but the result is strongly dependent from a threshold for basins contributing areas. We preferred using this dataset, homogeneous throughout Europe, obtained according to the scale of the area.

The crucial parameter to derive drainage density in a raster data from the drainage network is the size of the moving window of the focal density tool. We compared different maps considering increasing radius size, and concluded that a 2 km radius is the most suitable to represent the density of the streams and channels at a national scale, which is about the largest value used for focal statistics in this work. Eventually, the Dd layer was resampled at 500 m resolution to obtain a better representation of the spatial arrangement of the parameter, erasing redundant values (Fig. 1c).

4.4 | Variety Assessment

The variety, or diversity, of a raster map is defined for each cell as the number of different values of all the input cells within a specified neighbourhood around that location (moving window). The larger the number of different values within the moving window, the larger the variety. Specifically, we used circular windows in the focal statistic function in ArcGIS.

To select a radius for the moving window, we considered that the input variables considered here were available at different resolutions. We assumed that the lithological map should dictate the final scale for the GmI, since its resolution was the coarser one. In order to link the lithological data to the morphological processes, we calculated the mean area of the features in the lithological map, in each morphological cluster of Fig. 1d. We set the moving window radius to evaluate the landscape variability as the square root of the mean area, in each cluster. Table 2 lists the resulting values; the number of cells are obtained considering the working resolution of 25 m.

In our approach, each variable has the same weight in the final index, by construction. The output layers describing the variety of the input variables (slope, landforms, drainage density and lithology) were all reclassified into five classes (Fig. 4). We used the method of the natural breaks classification by Jenks Jenks (1967). Class breaks are such that groups with similar values are clustered together to maximize the differences between classes. The numerical values of the breaks for each input variable and for the final GmI map are listed in Table 3.

Eventually, the sum of the classified variety raster maps $\mathrm{Sp}_{\mathrm{var}}$ (slope), $\mathrm{Gm}_{\mathrm{var}}$ (geomorphons), $\mathrm{Dd}_{\mathrm{var}}$ (drainage density) and $\mathrm{Li}_{\mathrm{var}}$ (lithology) defines the geomorphodiversity index:

$$GmI = Sp_{var} + Gm_{var} + Dd_{var} + Li_{var} . \qquad (1)$$

The index defined in Eq. (1) potentially contains 20 different classes, by construction, stemming from the five classes in each of the input variety maps. The resulting raster map was

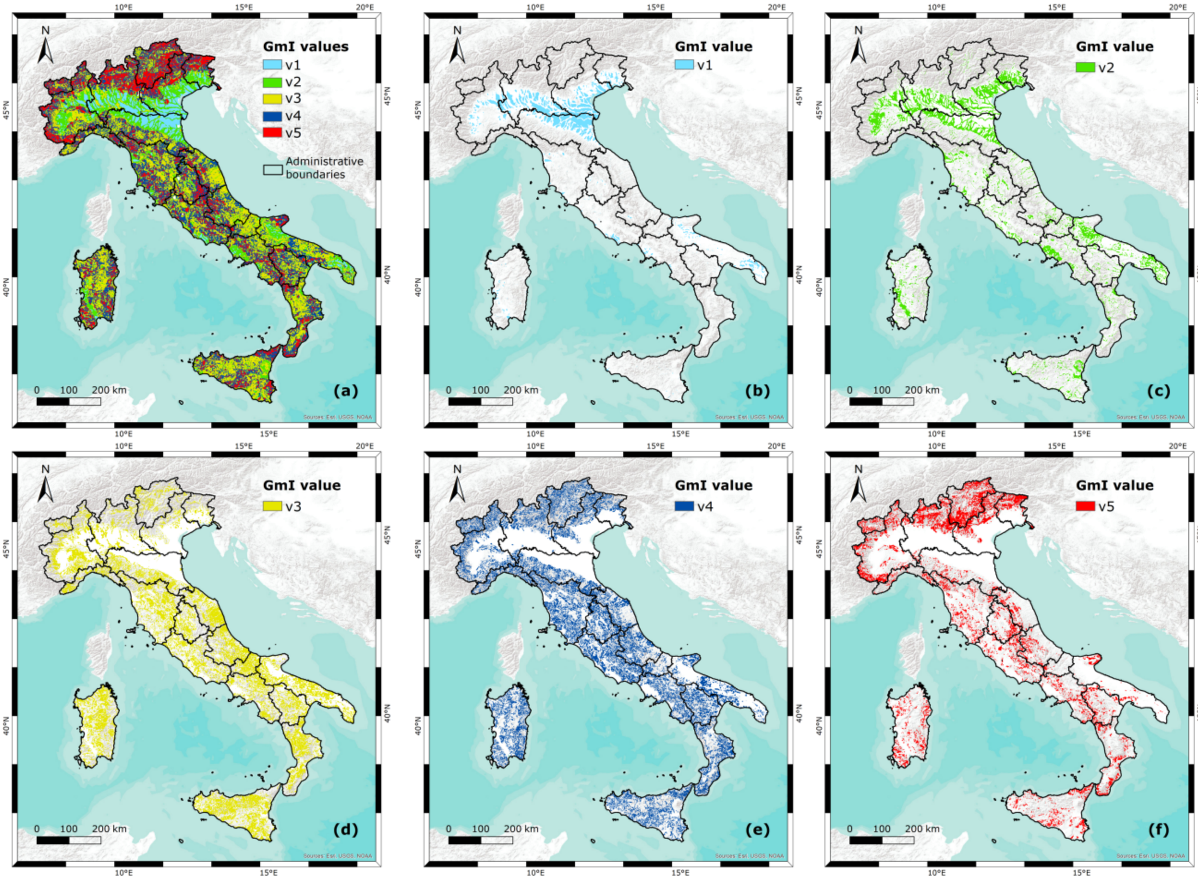

FIGURE 6 The spatial distribution of the GmI in Italy: (a) full GmI map (as in Fig. 5); (b)-(f) the five GmI classes distribution shown separately. Black lines show the administrative Italian boundaries (regions).

sampled at 500 m spatial resolution. For the sake of simplicity, we carried out a final reclassification of the final GmI into five land surface diversity classes, using the Jenks natural breaks algorithm (Table 3).

4.5 | Comparison with existing cartography

The cartographic elements in the geomorphological maps considered for "validation" of the GmI map were not homogeneous. An accurate evaluation of their spatial distribution required preparation of comparable, homogeneous datasets. The features in the regional datasets (polylines or polygons), were converted into point datasets. Vector datasets describing the geomorphological features in the test areas were converted in raster format with a cell size of 500 m snapped to GmI, and converted into a grid of points (the centres of the cells). This procedure allows us to obtain more than a single point for a polyline or a polygon, and to consider the size of each feature. Next, a density map assessment allowed us to create an output raster layer showing the number of features computed in a specific neighbourhood, whose size differs depending on the spatial distribution of the points. Eventually, we reclassified the density maps into five classes, in accordance with the GmI.

5 | RESULTS

Figure 5 shows the overall land surface diversity, or GmI, of Italy. Values in the map range from 1 (the lowest diversity) to 5 (the highest diversity). Figure 6 b–f shows the distribution of GmI raster values: value 1 represents 6.78 % of Italy; value 2, 14.35 %; value 3, 32.24 %; value 4, 30.95 %; value 5, 15.68 %.

As expected, the highest value of the index (5) is distributed along the most rough areas, whereas the lowest values (1 and 2), amounting to 20 % of the territory, are generally distributed in gentle slope zones. The values 3 and 4 of the GmI are represented throughout Italy, amounting around the 63 % of the entire territory. Figures 7, 8 and 9 show a comparison between distributions of values of the input variables (limited to lithology, slope and landforms) with the final map (GmI), to check for consistency and highlight existing patterns.

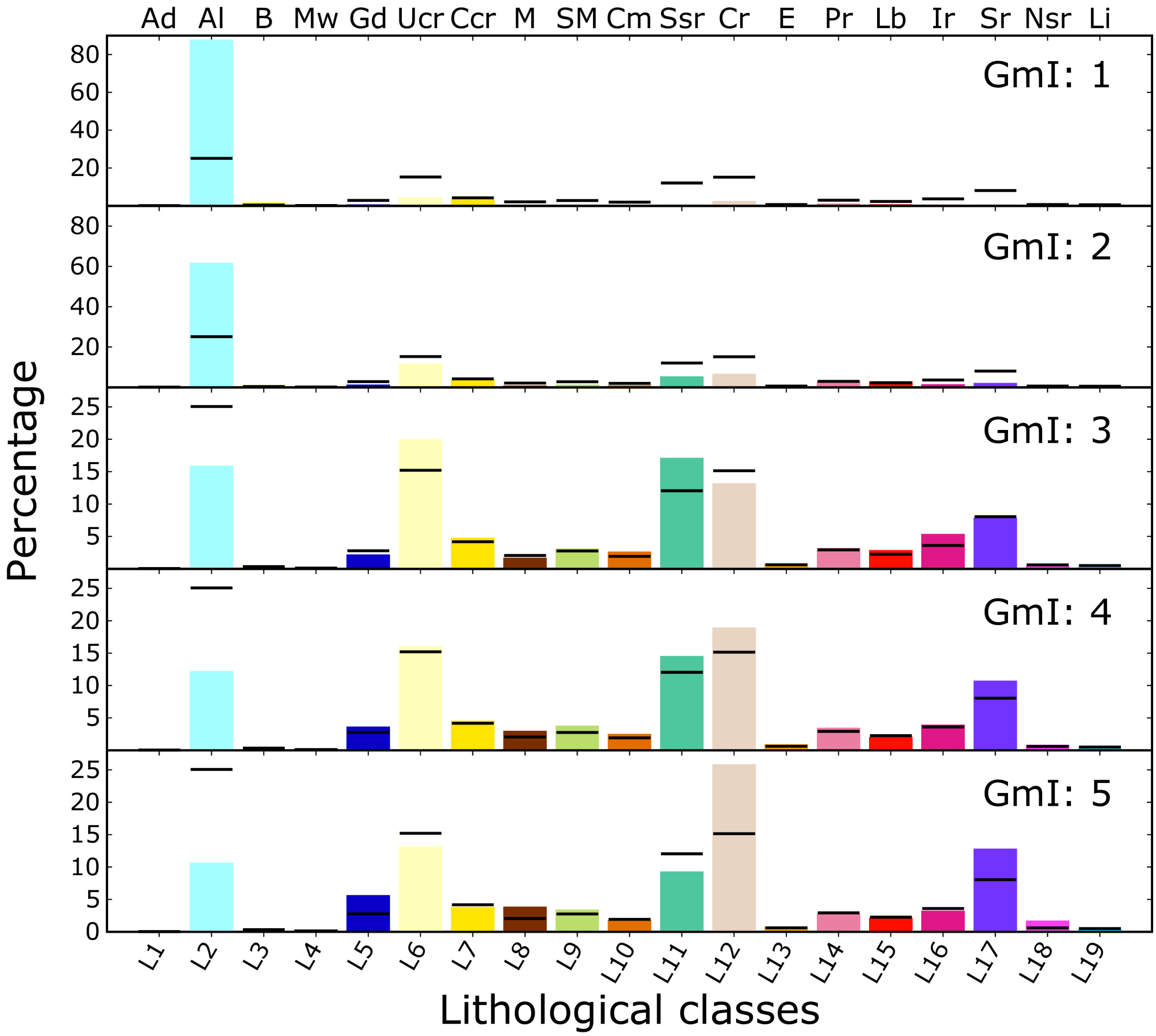

FIGURE 7 The distribution of lithology within each GmI class (1 through 5). Lithological classes are from Bucci et al. (2022). Full names are in **Table 1** and colours match the map in Fig. 1b. Black horizontal bars represent the national percentage of each class.

Figure 7 shows the percentage of lithological classes within each class of GmI. For each GmI class, the figure shows the national percentage Bucci et al. (2022) with horizontal black lines. Colours and classes in Fig. 7 match those in the map of Fig. 1b; class names are in Table 2. From the figure, it appears that GmI 1 and 2 consist almost entirely of alluvial plains (Al, L2); all the other classes are underrepresented with respect to the national values, especially for GmI 1. GmI classes from 3 through 5 contains a larger variety of lithologies, and a percentage of L2 much smaller than the national average. GmI 3 is mostly characterized by an excess, with respect to the national average, of unconsolidated clastic rocks (Ucr, L6), siliciclastic sedimentary rocks (Ssr, L11) and intrusive rocks (Ir, L16). GmI 4 shows excess of L1, carbonatic rocks (Cr, L12) and schistose metamorphic rocks (Sr, L17). Eventually, GmI 5 shows a strong dominance of Cr and Sr, while Ucr and Ssr are underrepresented.

Figure 8 shows the distribution of slope values within the five GmI classes; the log–scale insets help distinguishing the GmI specific distributions from the national reference. The distributions for GmI 1 and 2 are strongly peaked at zero slope; the histograms become less skewed for increasing GmI class; excess with respect to the national reference is mainly between 3° and 15° (GmI 3), 4° and 30° (GmI 4), and above 12° (GmI 5).

Figure 9 shows the percentage of landform classes (colours match those in the map of Fig. 1b) within each class of GmI. As for lithology and slope, for each GmI class, the distribution

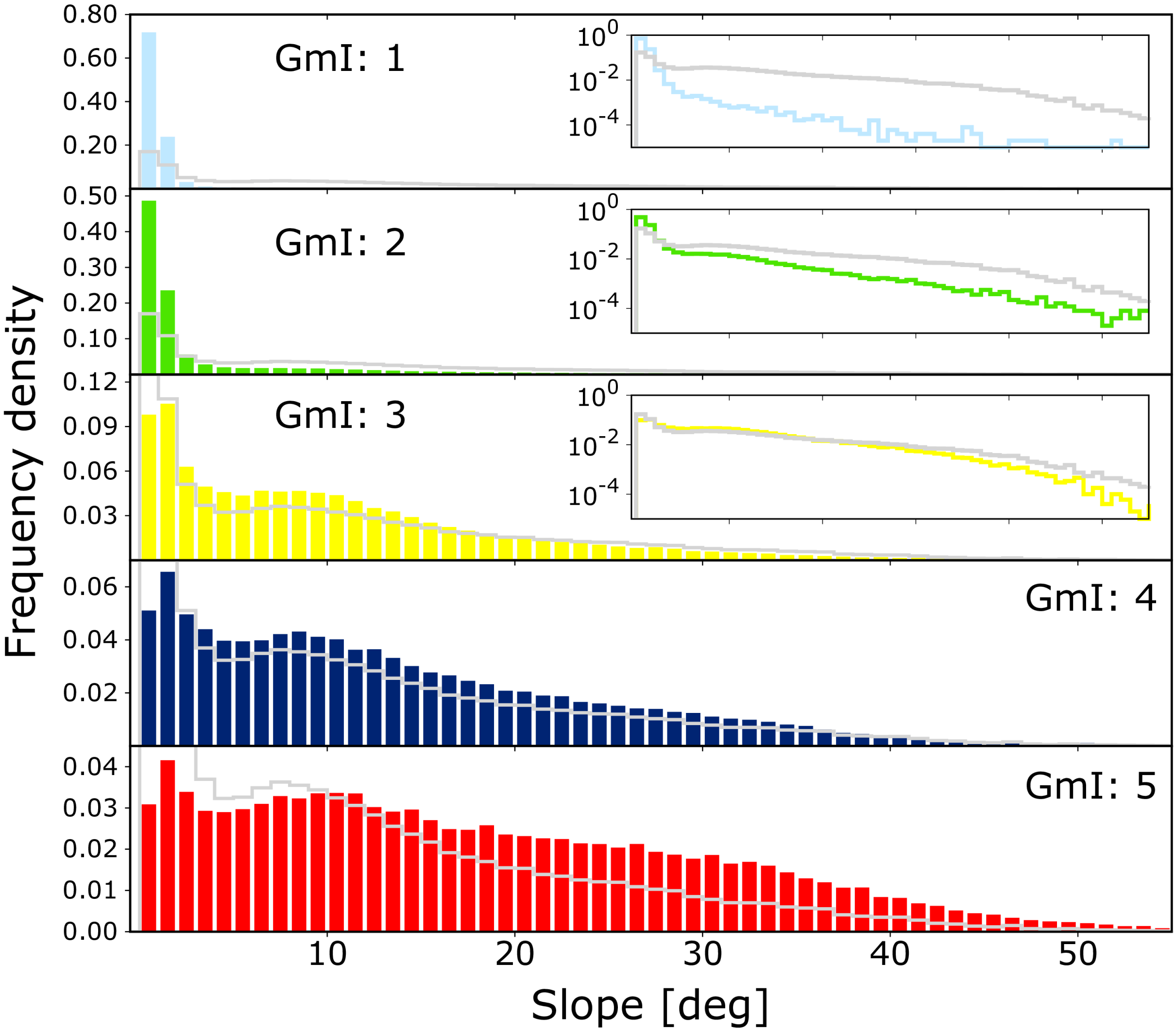

FIGURE 8 The distribution (frequency density, *i.e.*, normalized histograms) of slope values within each GmI class (1 through 5). Slope values calculated at 25 m resolution, from EU-DEM elevation data, and distributed in one–degree bins. For each GmI class, grey histograms show the national distribution of slope. The insets show the same distribution for the corresponding class, in log scale. Colours of GmI classes match those in Figs. 4 and 5.

is compared with the national reference value. In agreement with the case of Figs. 7 and 8, we can clearly see that GmI 1 mostly consists of flat landforms (FL). Flat areas are also in excess for GmI 2, along with shoulders and footslopes. The classes GmI 3 through 5 show excess of all of the classes but flat landforms. The main difference for increasing GmI class is the decrease of Fl class, and increase of valley class (VL).

Concerning the "validation" step, we investigated the numerical difference between the values of the reclassified density maps obtained from the geomorphological datasets (Section 3.4) and the GmI (Fig. 2).

Figure 10 shows the results of the comparison step. The different colours help visualize the difference between the density maps and GmI; black (value 1) corresponds to larger discrepancies, yellow (value 2) to moderate differences, and green (value 3) to little disagreement. The vast majority of cells fall within green or yellow classes, confirming the effectiveness of the GmI in the selected areas.

The comparison in the Lombardy region (Fig. 10b) showed the largest presence of value 1, whereas comparison in the other regions showed a better match between GmI and geomorphological maps. The cartography for the Lombardy region shows several features even in flat areas, where Dd and Lt are the only relevant components of the GmI.

The poor performance in flat areas confirms the need to improve the model in plains. Undoubtedly, the GmI in this morphological context is low, and it should be further discriminated

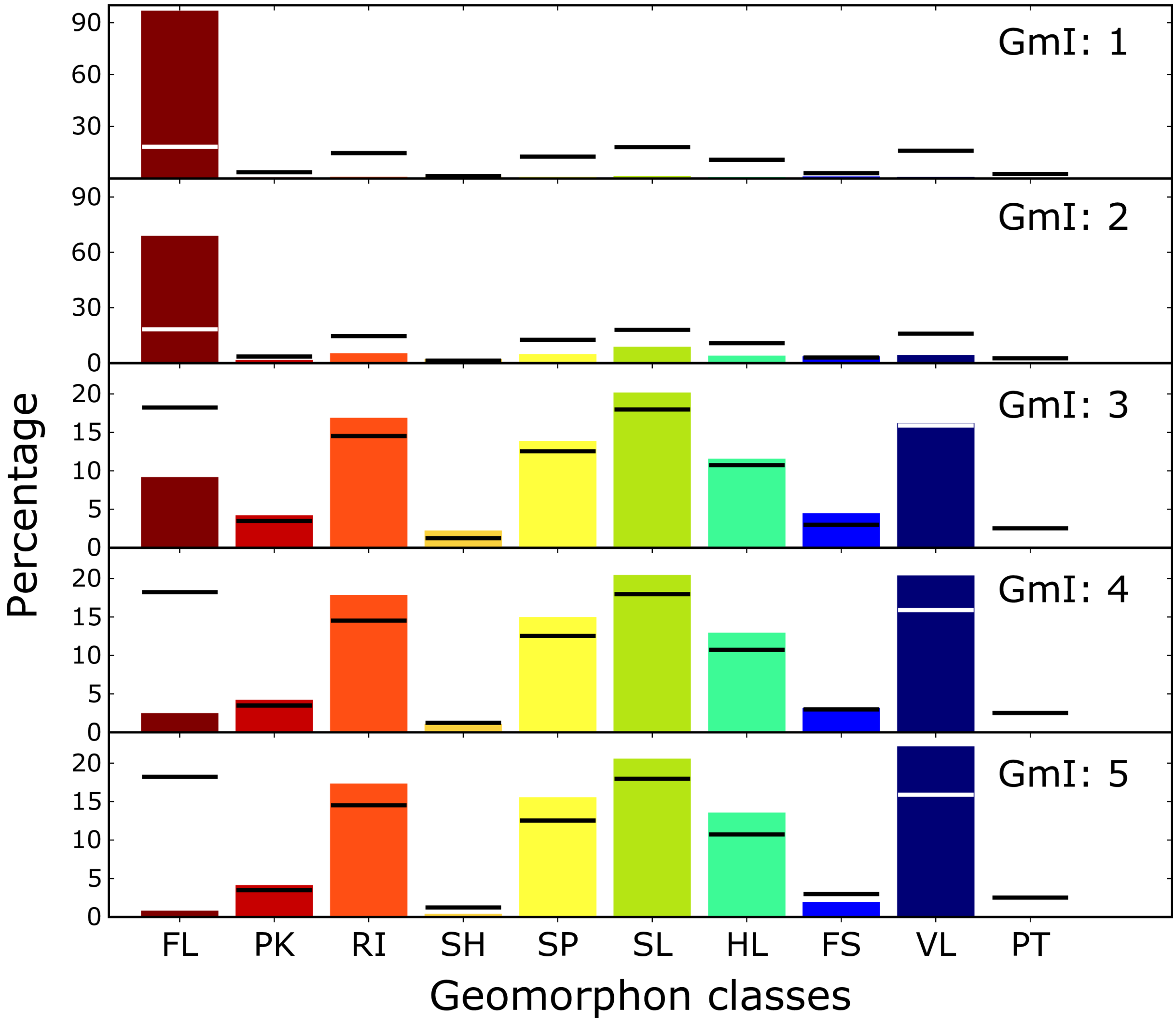

FIGURE 9 As in Fig. 7, but for landforms. FL: flat; PK: peak; RI: ridge; SH: shoulder; SP: spur; SL: slope; HL: hollow; FS: footslope; VL: valley; PT: pit Jasiewicz and Stepinski (2013).

and improved. In Piedmont and Apulia (Fig. 10a and Fig. 10d, respectively), the largest part resulted in a good match with the GmI and only few pixels have a little difference with the index (value 2). The opposite holds for Lombardy and Umbria (Fig. 10c), where the frequency of values 2 and 3 were almost equivalent. However, in those cases either the value 2 areas lacked geomorphological features and the GmI have middle–high values, or the areas have several features, but the landscape is mostly flat resulting in a low value index.

The validation procedure, which is original to this work, demonstrated that the GmI describes pretty well the geomorphological variability of the tested regions.

6 | DISCUSSION

The proposed land surface diversity GmI to describe the variability of a landscape was inspired by previous works proposed by Serrano Cañadas and Ruiz Flaño (2007), Benito-Calvo et al. (2009), Serrano Cañadas et al. (2009) and Melelli et al. (2017). We assumed that the morphometric parameters introduced in those works are the main factors for the identification of geomorphological features, together with the lithological complexes, which affects the terrain response to the exogenous agents.

In our approach, each variable has same weight. Raster input data has 25 m resolution, and thematic data has 1:100,000 geographical scale. The final GmI map contains five classes, and has a resolution (Fig. 5) of 500 m, which fits well for our

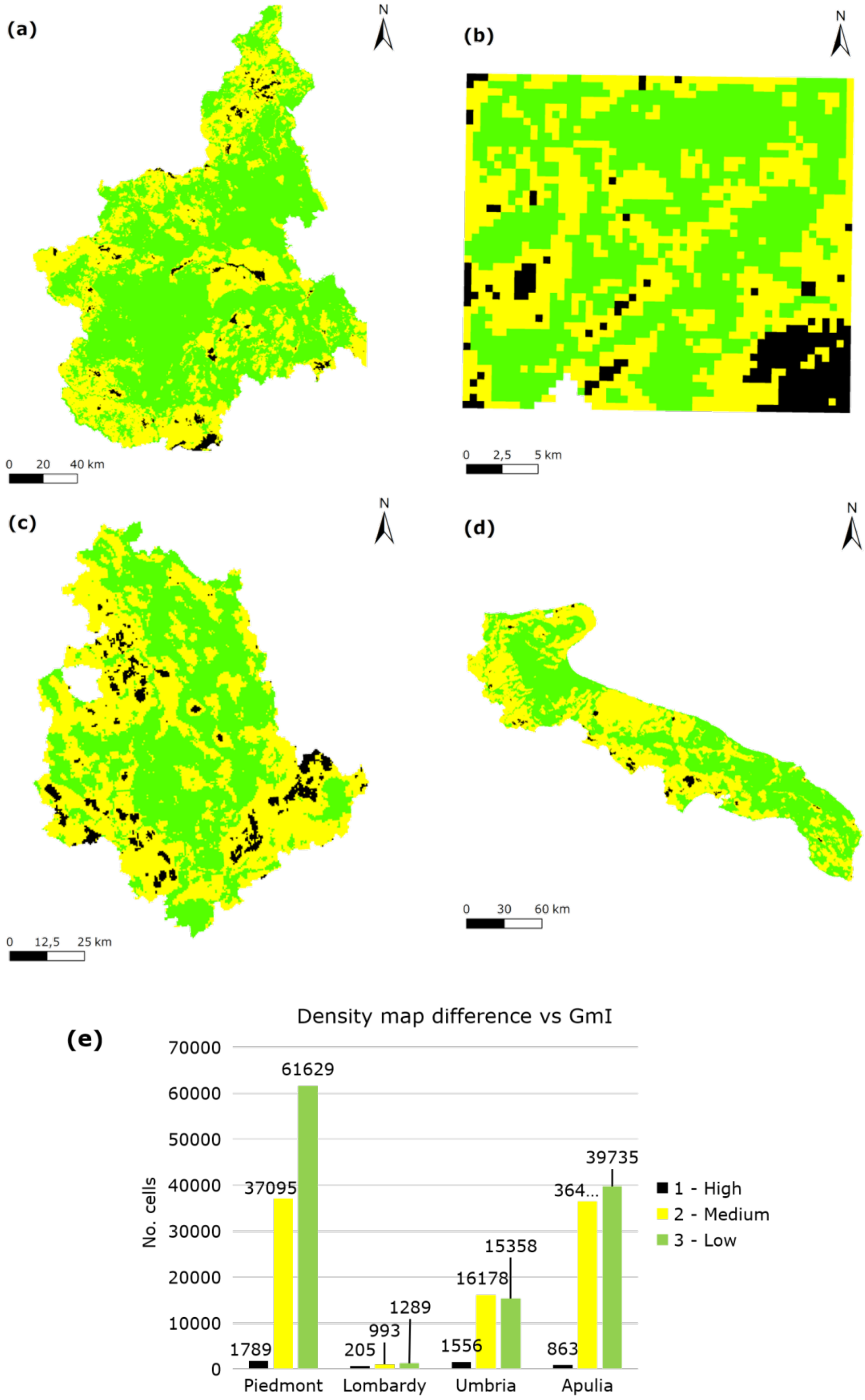

FIGURE 10 Validation results in the four areas shown in Fig. 6: (a) Piedmont, (b) Lombardy, (c) Umbria, and (d) Apulia; (e) histogram displaying the density map difference with our GmI, in each area. Values from 1 through 3 represent increasing degree of match.

purpose of studying geomorphodiversity at national scale, and nicely represents the diversity of the Italian physical territory.

One relevant characteristic of the GmI presented here is that it relies on some good quality input dataset. The DEM supplied by Copernicus is based on SRTM and ASTER GDEM data fused by a weighted averaging approach. The lithological information of Bucci et al. (2022) is the latest and the most complete dataset available for the Italian territory, at this scale. One advantage is that reproducibility of the approach on a different geographical area only depends on availability of equivalent input datasets.

The issue of spatial resolution, and of related quantities such as the size of neighbourhoods to calculate DEM–derived quantities and the size of moving windows to calculate diversity indices (also known as focal statistics) was approached in the least possible subjective way. In fact, parameters governing the selection of landforms were linked to the average size of slope units, in each topographic cluster defined by Alvioli et al. (2020). The cluster classification also suggested the use different sizes for moving windows (dictated by the resolution of the lithology layer) to calculate variety. We did not perform an explicit assessment of the effect of using different values of these parameters beyond these assumptions, here.

The GmI map was tested assuming "traditional", regional geomorphological maps as "ground truth". A complete and homogeneous geomorphological dataset would have been preferable, but this information is not available for all the Italian regions, and even if a common and homogeneous approach exists for the definition of the geomorphological dataset, the Italian territory is far from being completely covered by a unique and complete geomorphological mapping Najwer et al. (2022). Thus, we relied on the free access geomorphological maps provided by regional administrations. The particular choice of the maps in Fig. 2 was dictated by a few but relevant characteristics. The four areas are somewhat representative of different geographical and climatic settings in northern, central and southern Italy. Moreover, the areas contain heterogeneous lithotypes in different geodynamic contexts, representing different endogenous assumptions for the geomorphic agents.

From the validation step, we can conclude that the assumptions were reasonable, given that all of the selected areas contain the full range of GmI classes, denoting a meaningful comparison between GmI and the geomorphological layers. Nonetheless, further validation of the proposed GmI quantitative procedure is desirable.

The density maps in Fig. 11 show that areas with the highest values of GmI matched a few key areas in the Italian natural heritage (Fig. 11a): (i) the Dolomites, recognized as one of the Italian alpine areas of greatest natural interest, including nine natural parks, and declared an UNESCO World Heritage Site in 2009 Panizza (2009); (ii) in the Apennines, a significant area located on the border between Umbria, Marche, Lazio and Abruzzo regions, including two national parks (Monti Sibillini National Park and Gran Sasso National Park) as well as three other valuable areas, also of interest for their geological and naturalistic heritage Farabollini et al. (2005), Miccadei et al. (2011), Piacentini et al. (2011).

As expected, the areas with lower values of GmI correspond to the central eastern part of the Po Valley (Fig. 11b).

However, these results must lead to a further understanding of geomorphodiversity. Even if it is obvious that in gentle slope areas the variety of geomorphological processes and their efficiency in shaping the landscape are lower than in roughened areas, it is also true that in flat areas, as the alluvial plains, some relevant landforms are still evident and geomorphological processes (*i.e.*, fluvial) have a sizable effect.

To distinguish geodiversity in morphological contexts such as alluvial plains we introduced drainage density; an index that neglects the latter would be uniform in large flat areas. Considering additional input parameters may help refining the GmI and improve the understanding of abiotic features in these areas. In fact, a simple comparison of GmI with a biodiversity index reveals a mismatch in flooding-prone, the deltaic areas and coastal areas, which are sites of strategic importance for biodiversity Jona Lasinio et al. (2017), Capotorti et al. (2020).

7 CONCLUSIONS

We obtained a land surface diversity index -— namely, GmI – from lithological, morphological and hydrographic features. The selection of input parameters aims at standardizing endogenous factors and exogenous modelling agents that are the basis for the creation and evolution of the physical landscape, landforms and morphological processes.

Geomorphodiversity is a part of geodiversity, and it represents a key parameter for understanding the different morphological settings and the evolution of a landscape. The spatial and temporal dependence of biodiversity from geodiversity was established, and therefore a quantitative assessment of geodiversity is relevant for sustainable management of the territory.

The results obtained in this work allow drawing the following conclusions. First, the use of a minimal set of heterogeneous data, namely elevation and lithological data, is sufficient to obtain a validated land surface diversity index, in a reproducible way. Second, relating characteristic spatial scales and processing parameters to the resolution of available data, and to existing local terrain classifications, is an effective way to solve the issue of free parameters in an objective way. Third, account of drainage density among the input quantities introduce an effective handle to evaluate land surface diversity in flat areas, where all of the morphometric and thematic quantities fail to distinguish between different local characteristics. In addition, geomorphological maps compiled in a traditional

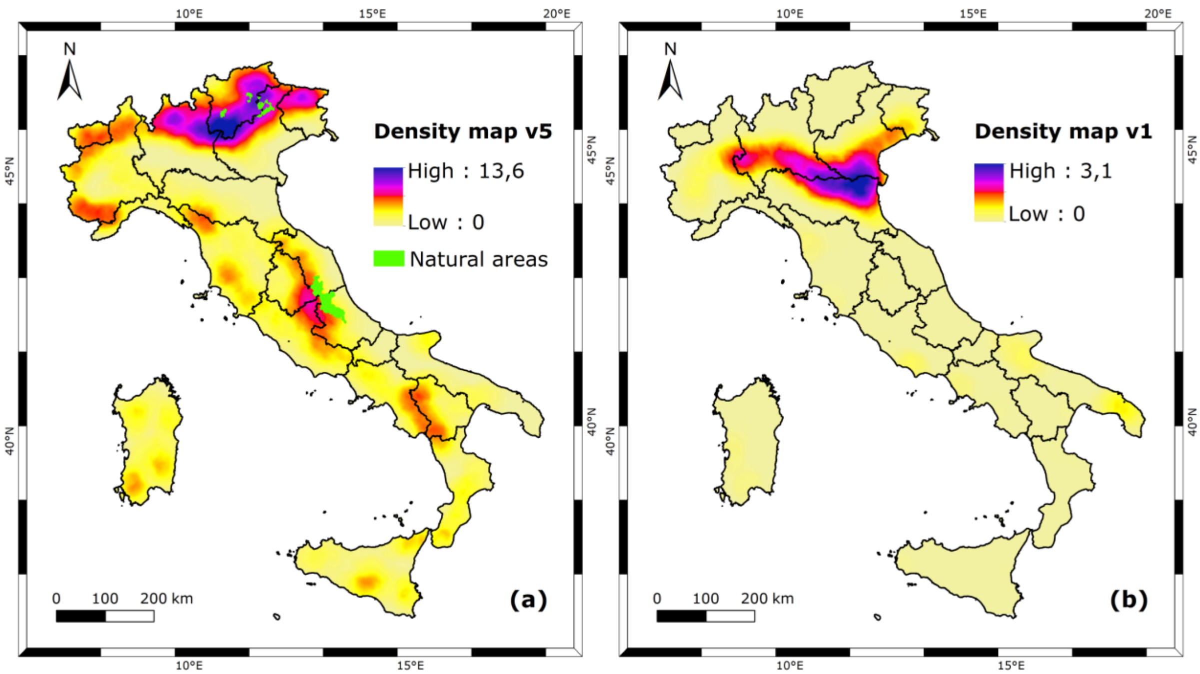

FIGURE 11 Density maps of the maximum (a) and minimum (b) values of the GmI. The GmI 5 value (v5) density map matches key areas in the Italian natural heritage, including much of the Dolomites mountain range in the Northern Italy, the Monti Sibillini National Park and the Gran Sasso National Park in the central Apennines. The density map of the GmI 1 value (v1) highlight the highest values along the central eastern part of the Po Valley.

way are effective tools to validate a quantitative, spatially distributed index in specific areas: validation was overlooked in the relevant literature, with a few exceptions.

A future step might be to include rivers, lakes and marsh processes at a finer scale to extend further the applicability of geomorphodiversity index. In fact, although the hydrographic network used here compensated for the topographic factor in the lowland areas, it is probably inadequate for evaluating the contribution of geomorphological processes on alluvial plains and lacustrine and palustrine environments to geomorphodiversity.

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AUTHOR CONTRIBUTIONS

Martina Burnelli wrote the initial draft of the paper and made substantial contribution to the design of the work. The Author performed the analysis, together with Massimiliano Alvioli for the subdivision in topographic units and for the classification of landforms and contributed to the methodological approach. The Author validated the results. She edited all the figures. Laura Melelli performed the analysis for the drainage density, the topographic parameters, the final GmI assessment and the density maps in the conclusion. The Author reviewed the entire paper. Massimiliano Alvioli performed the analysis and contributed to the methodological approach. The Author reviewed the entire paper. All the Authors revised the work critically for important intellectual content and approved the version to be published. All the Authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICT OF INTEREST

The authors declare no potential conflict of interests.

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