Using geoinformatics and geomorphometrics to quantify the geodiversity of Crete, Greece.

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Abstract

The geodiversity of Crete is quantified in this study, based on the classification of geomorphometric, geological and climatic factors. A number of geomorphometric variables, extracted from the ASTER Global Digital Elevation Model (ASTER G-DEM) in conjunction with geological and climatic information, are evaluated through various algorithms incorporated into Geographical Information System (GIS) software’s. The derived geoinformatic data sets are
then analyzed to produce the geodiversity of Crete. The geodiversity map is used to quantify the geodiversity, by calculating landscape diversity and other spatial pattern indices. Those indices are evaluating the richness, evenness, fragmentation and shape of the landscape patch types. The outcome of this study has highlighted that western Crete is characterized by complex geodiversity with more irregular, elongated and fragmented landscape patterns relative to the eastern part of the island. The geodiversity indices provide insights into the processes shaping landscapes, particularly the "battle" between neotectonic landscape deformation and erosion/deposition. The methodology presented can be useful for decision makers when evaluating a regions geological heritage, planning the management of natural resources, or designating areas for conservation.

**Keywords:** Geodiversity; geomorphometrics; landscape indices; geoinformatics; ASTER G-DEM.

### 1. Introduction

Various physical properties of the Earth’s surface are factors that influence local topography, with geomorphometric landform information providing valuable knowledge regarding the interfered processes shaping landscapes and producing geodiversity (Nieto, 2001; Benito-Calvo et al., 2009). Gray (2004) defined geodiversity as: “The natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landform processes) and soil features. It includes their assemblages, relationships, properties, interpretations and systems.” Kozlowksi (2004), added surface waters such as lakes and rivers, as well as including the impact of human
influence on geodiversity. Sharples (2002) also considered the interrelated character of the assemblages, properties, systems and processes of the geological, geomorphological and soil elements that produce geodiversity. The geodiversity concept has been used in various applications such as geological heritage, geoconservation, ecosystem management, etc (e.g. Gray, 2004; Carcavilla et al., 2008; Gordon et al., 2012; Stavi et al., 2015). The subject of geodiversity has not been as widely well-established or used as a biodiversity concept. So it follows that the abiotic diversity of Earth remains a relatively challenging domain to assess both qualitatively and quantitatively (Pereira et al., 2013).

Although the concept of geodiversity has been widely discussed, there are relatively few publications on the quantification of geodiversity (e.g. Bruschi, 2007; Serrano and Ruiz-Flano, 2007; Benito-Calvo et al., 2009; Ruban 2010). Pioneering work involving the classification of geodiversity was carried out in the development of land systems mapping (Christian and Stewart, 1952; Ollier et al., 1969) and by researchers analyzing landscape parametrics (e.g. Leopold, 1969; Conacher and Dalrymple, 1977). However there has been a resurgence of geodiversity research in recent years due to improved computing and software functionality, which via the geoinformatics has provided a useful tool for managing natural resources, human resources and natural hazards (e.g. Serrano and Ruiz-Flano, 2007; Parks and Mulligan, 2010; Hjort and Luoto, 2012; Rawat, 2013). Investigating heterogeneity in geological and geomorphological properties can lead to the quantification of landscapes and towards a better understanding of their complexity (Nieto, 2001; Panizza and Piacente, 2008). Physical elements such as geomorphological and geological attributes, constitute the main geodiversity elements in its assessment (Kozlowski, 2004; Serrano and Ruiz-Flano, 2007). A combination of geological, geomorphological, climatic or hydrological information using geoinformatic approaches can be
useful in the quantification of geodiversity for a regional scale (Benito-Calvo et al., 2009; Hjort and Luoto, 2010).

This study aims to assess the geodiversity of Crete, one of the most tectonically active areas in the world (Pirazzoli et al., 1996). The region is characterized by a high degree of neotectonic activity which is the main triggering agent for the development of a complex heterogeneous terrain (Shaw et al., 2008). In order to assess and describe the abiotic heterogeneity, this study quantifies the geodiversity of Crete, based on a regional geodiversity map that includes geomorphometric, geological, hydrological and climatic information. Such information can constitute the main factors in evaluating the geodiversity of a region, adopting the methodology of Benito-Calvo et al. (2009), which is partly modified to fit the needs of this study.

The small number of variables used by Benito-Calvo et al. (2009) to study the tectonically more “quiet” region of Spain in comparison to Crete, leaves scope for more geomorphometric indices to be used for a deeper investigation of the geomorphological, hydrological and morphotectonic context of Crete. The final geomorphometric classification of this study considers additional hydrological and morphotectonic indices that Benito-Calvo et al. (2009) did not use in their study. The geomorphometric classification was based on geomorphometric indices (amplitude of relief \( Ar \), stream length gradient \( SL \), stream frequency \( Fu \), drainage density \( Dd \), elevation relief \( Er \), topographic wetness index \( TWI \), slope gradient \( Sg \), surface area/ratio \( SAR \), dissection index \( Di \)); all derived from the ASTER G-DEM, a freely-available digital elevation model with 30m pixels. The geomorphometric indices were spatially analyzed to provide a map of geomorphometric classes. The geological classification was based on digitized 1:50,000 scale geological maps (IGME, 1971), with the
geological classification simplifying litho-chronologically, the initial complex formations of the IGME (1971) geological maps. The climatic classification consisted of seasonal average temperature and rainfall raster data layers for the period 1930-2000, determined by the EMERIC project (Sarris, 2007; Fassoulas et al., 2007). Two different widely used approaches were tested in this study, the one by Chorley et al. (1984) for evaluating morphogenetic regions and the one of Kottek et al. (2006) providing an update of Köppen-Geiger studies for climatic zones determination (Köppen, 1936; Geiger, 1954). The results of the Chorley et al. (1984) approach did not show significant variation of morphogenetic regions, with almost the whole island being characterized as “arid” so the Kottek et al. (2006) methodology was preferred, offering a larger variance of climatic zones across Crete. Each of the aforementioned classifications, presented in detail below, were implemented using GIS softwares to obtain a regional geodiversity map of Crete, via an overlay union procedure (Benito-Calvo et al., 2009). In that way, all geodiversity components were assessed equally, avoiding overestimation of any particular components (Pereira et al., 2013).

Landscape metrics were then applied on the geodiversity map to quantify the geodiversity, following Benito-Calvo et al. (2009). This study used calculations of diversity indices which can determine the heterogeneity of landscapes, via indices such as the Patch Richness Density (PRD), Shannon’s Diversity Index (SHDI), Shannon’s Evenness Index (SHEI), Simpson’s Diversity Index (SIDI) and Simpson’s Evenness Index (SIEI). In the study of Benito-Calvo (2009), they acknowledge that the combination of the aforementioned diversity indices with other spatial pattern indices will lead to better comprehension of the landscape spatial configuration. For this reason additional spatial pattern indices, such as: i) shape index (SHAPE); ii) proximity index (PROX); iii) related circumscribing circle (CIRCLE); iv) patch density (PD)
and; v) perimeter-area fractal dimension (PAFRAC), were also calculated to evaluate the landscape form regarding the shape and fragmentation characteristics. Those indices were analyzed using Fragstats spatial pattern analysis freeware (McGarigal et al., 2002). The quantification, classification and mapping of geological, geomorphological, hydrological and climatic factors, can improve our understanding of the processes and materials that have controlled landscape evolution across Crete. Such knowledge is new for the region offering valuable information to various scientific fields for decision making, such as land use mapping, geological heritage, environmental management or nature conservation.

2. Study area

Crete lies within the emergent outer fore-arc of the largest and most active subduction zone in Europe, the Hellenic arc and is therefore characterized by high rates of tectonic activity and seismicity (Papazachos and Comninakis, 1978; Kelletat, 1996; Pirazzoli, 2005) (Fig. 1). By way of an example, the 21 July AD 365 earthquake (Mw 8.3-8.5), the “Early Byzantine Tectonic Paroxysm”, produced co-seismic uplift up to 9 meters on southwestern Crete (Pirazzoli et al., 1996; Stiros, 2001; Shaw et.al., 2008). The island is characterized by low to medium elevation (up to ~900m) on its northern coast and high elevation (up to ~2500m) with steep slopes on the southern coast, with N-S trending deeply incised valleys (Fytrolakis, 1980; Sarris, 2005). Two large massifs, the Lefka Ori and Psiloritis mountains, are found in the western and central part of the island, with peaks of up to ~2500 m (Fig. 1: labeled as LO and P respectively). The geological and tectonic setting of the island was initially investigated in the early 1950s (Papastamatiou & Reichel, 1956; Papastamatiou et al., 1959). These studies indicated the presence of two major nappes, the Pindos nappe overlying the Tripolis nappe
These units belong to the external Hellenides and were deformed after the deposition of flysch formations in the Late Eocene-Oligocene (Renz, 1955; Aubouin and Dercourt, 1970). Further work in the 1970s established a better tectonostratigraphic framework for Crete by indicating the presence of several nappes, either below the Tripolis unit or above the Pindos nappe (Seidel, 1971; Baumann et al., 1976). The geological setting of the island of Crete is very complex and it is characterized by pre-Alpine and Alpine rocks (composing a pile of nappes) and post-Alpine rocks (Neogene and Quaternary sediments) (Fig. 2). In the case of pre-Alpine and Alpine rocks, the Cretan nappe pile consists of two nappe groups: i) the upper nappes (Tripolis, Pindos, Uppermost) and; ii) the lower nappes (Plattenkalk, Trypali, Phyllite/Quartzite). In the post-Alpine rocks, the sediments of Crete can be divided into six groups: i) Prina group, ii) Tefeli group, iii) Vrysses group, iv) Hellenikon group, v) Finikia group, and vi) Agia Galini group (Meulenkamp et al., 1979).

3. Methods and Datasets

3.1 Regional Geodiversity

i) Geomorphometric classification

In order to determine geomorphometric classification, several geomorphometric variables extracted from the ASTER G-DEM were evaluated (Fig. 3). In a similar study, Benito-Calvo et al. (2009) examined only the variables of elevation, slope, tangential curvature and roughness to perform a geomorphometric classification. In order to highlight additional geomorphological, hydrological and morphotectonic information for this tectonically active region, various other variables were analyzed in this study. The geomorphological information was mainly derived by
indices, such as SAR, Sg, Er and Di, highlighting the terrain roughness, dissection, concavity or convexity (Singh and Dubey, 1994; Jenness, 2004; Rowberry, 2012) (Fig. 4). The morphotectonic information was contributed prior by indices such as Ar, SL (Ciccacci et al., 1988; Toudeshki and Arian, 2011) (Fig. 4). Some supplementary indices such as Dd, Fu and TWI were acknowledged to provide hydrological information while their interrelation can also highlight both geomorphological and morphotectonic information (Kouli et al., 2007; Argyriou et al., 2016) (Fig. 4). The indices to be used in the geomorphometric classification were derived after prior evaluation of the low interdependency of various DEM derivatives by selecting the non-correlated ones (Table 1). The following geomorphometric indices and their contributed geomorphological, hydrological and morphotectonic information were considered:

The amplitude of relief (Ar) is the maximum difference in elevation within unit areas, in this case, 1 km^2 (Ciotoli et al., 2003) (Fig. 4). Ar is useful for assessing active tectonics to determine recent vertical displacements (Ciccacci et al., 1988; Troiani and Della Seta, 2008) and can also be used to determine fluvial erosion (Della Seta et al. 2004). Following the method of Della Seta et al. (2004), the relative relief was determined by subtraction of the ASTER G-DEM_{max} (each output cell contains the maximum of the input cells that are encompassed by the extent of that cell) from the ASTER G-DEM_{min} (each output cell contains the minimum of the input cells that are encompassed by the extent of that cell), within a grid of 1×1 km cells (Argyriou et al., 2016). The Ar values were determined by the centroid points of each unit area, while kriging was used as the interpolation method, to produce a spatial distribution map of Ar (Troiani and Della Seta, 2008). The higher values of the Ar index imply to vertical displacements of uplifted or subsidence blocks, while regions with no intense landscape deformation are highlighted by their low values (Ciccacci et al., 1988; Argyriou et al., 2016).
The stream length gradient (SL) shows the change in elevation of a reach, relative to the length of that reach, multiplied by the total length of the channel from the point where the index is being calculated (Hack, 1973; Keller, 1986; Toudeshki and Arian, 2011) (Fig. 4). Tectonic activity and rock resistance to erosion are the main factors that can be investigated using the SL index (Keller and Pinter, 1996; Garcia-Tortosa et.al, 2008). Any abrupt changes in the gradient of river will be revealed by the high values of the SL index and can be linked to active tectonics, while lower index values imply a fine drainage network without any influence of landscape deformation (Garcia-Tortosa et.al, 2008). The stream network was delineated from the ASTER G-DEM, by filling the voids using the D8 algorithm and the ArcGIS hydrology module to extract drainage network. A flow accumulation threshold value of 400m$^2$ provided the best fit for drainage network delineation, based on examination of satellite images, aerial photographs and topographical maps to determine vegetation corridors along floodplains (Tarboton et al., 1988; Maidment, 2002; Li, 2014; Argyriou et al., 2016).

Stream frequency (Fu) evaluates the total number of the stream segments to the area of the basin (Horton, 1945) (Fig. 4). The values of Fu indicate the degree of slope steepness, rock permeability and surface runoff. High Fu values (>5) are associated with impermeable surface material, high relief and low infiltration capacity, while low Fu values imply permeable surface material, low relief and high infiltration capacity (Reddy et al., 2004; Ozdemir and Bird, 2009; Bagyaraj and Gurugnanam, 2011). The high Fu values can be indicative for areas with coarse drainage network and with the distortion of the drainage system being a result of neotectonic forces (Kouli et al., 2007). This index was calculated within a GIS software package by using kernel density within a search area of 2 km for the derived drainage network (Zavoianu, 1985; Kouli et al., 2007).
Drainage density ($Dd$) determines the total stream length, relative to the area of the basin (Horton, 1945) (Fig. 4). $Dd$ provides information about surface runoff potential, the degree of landscape dissection, rock permeability and resistance to erosion can be assessed (Verstappen, 1983; Tucker and Bras, 1998; Mesa, 2006). $Dd$ is controlled by factors such as slope gradient and relative relief: low values (ie, < 5) are associated with a coarse drainage network, low relief, permeable surface material and terrain with long hill slopes (Berger and Entekhabi, 2001; Sreedevi, 2009). High $Dd$ values indicate fine drainage texture, high relief, impermeable surface material and a dissected terrain (Strahler, 1964; Awasthi et al., 2002).

Elevation relief ($Er$) describes rugosity in a continuous raster surface and provides hypsometric information about a watershed (Pike and Wilson, 1971) (Fig. 4). It is equivalent to the hypsometric integral and can indicate the degree of disequilibrium in the balance of erosive and tectonic forces (Strahler, 1952, 1958; Luo, 1998; Keller and Pinter, 2002). The $Er$ indicates the degree of landscape dissection (Clarke, 1966; Evans, 1972). Using $Er$, it is possible to discriminate lowland plains and dissected upland plateaus in a manner that cannot be achieved using slope angle or relative relief. A value near to 0 is indicative of concavity or sub-horizontal terrain with some isolated peaks, whereas a value near to 1 is indicative of convexity or sub-horizontal terrain with deep incision (Rowberry, 2012).

The Topographic Wetness Index ($TWI$) evaluates the soil moisture and surface saturation that is influenced by the changes in slope position such as shedding slopes or receiving slopes (Beven and Kirkby, 1979; Sorensen, 2005) (Fig. 4). The accumulation of water at the foot of slopes leads to a straight dependent relation with this index. It can also identify regions with low values indicating: i) V-shaped valleys characterized by high incision; ii) high relief surfaces where moisture accumulation exists in lower degree and; iii) longitudinal ridges. The higher
values of the index can assess regions consisting of: i) low gradient surface and moisture accumulation at higher degree, or ii) alluvial deposits (Migon et al., 2013). The TWI can be useful in evaluating land surface water distribution due to topographic changes and landscape deformation (Anderson and Kneale, 1982; Hjerdt et al., 2004; Argyriou et al., 2016).

*Slope gradient* (Sg) shows the change occurring in elevation between each cell and its neighbors (ESRI, 2003) (Fig. 4). Flat surfaces are characterized by low values while a steep relief is indicated by the higher values.

The *surface area/ratio* (SAR) generates a surface area and surface ratio raster layer from the ASTER G-DEM data (Fig. 4). The cell values for the new raster reflect the surface area and the surface ratio (surface area / planimetric area) for the land area contained within that cell's boundaries (Jenness, 2004). They provide useful indices of topographic roughness and convolutedness, giving a more realistic estimate of the land area available in relation to the simple planimetric area (Berry, 2002; Jenness, 2004). Surface area grids may easily be standardized into SAR grids by dividing the surface area value for each cell by the planimetric area within that cell. High values of SAR will indicate a rough and dissected terrain while lower index values will highlight smoother ones of low roughness (McAdoo et al., 2004).

The *Dissection index* (Di) is the ratio between absolute relief and relative relief, indicating the degree of dissection or vertical erosion (Singh and Dubey, 1994) (Fig. 4). It is a useful index for the study of terrain dynamics and landscape evolution, particularly the interaction between erosion and deposition (Mukhopadhyay, 1984; Sen, 1993). Low values of Di indicate lack of vertical dissection/erosion and hence dominance of flat surface, while high Di values suggest highly dissected terrain with vertical escarpment of hill slope (Pareta et al., 2011).
Many researchers have shown that the aforementioned indices are effective indicators of the Earth’s surface processes driving landscape evolution (e.g. Currado and Fredi, 2000; Jamieson et al., 2004; Toudeshki and Arian, 2011). A correlation coefficient matrix has been produced to validate the low interdependency of the nine selected variables (Table 1). The correlation coefficient matrix showed that the indices were characterized by low correlation to each other (values <0.6). Consequently, selected indices can provide a range of variant information regarding the geomorphological, hydrological and morphotectonic context to the final geomorphometric classification.

The next step of the analysis was to carry out a geomorphometric classification of the nine variables using the Interactive Self-Organizing Data Analysis Technique (ISODATA) algorithm. In this stage, clustering of the multivariate data takes place using an initial clustering with a large number of classes, in order to determine the characteristics of the natural grouping of cells (Benito-Calvo et al., 2009). A clustering histogram analysis, with an initial cluster of 90 classes, was selected for the nine variables (Fig. 5B). The number of classes was ten times larger than the nine variables being used herein, following Benito-Calvo et al. (2009), where 40 classes were considered for the four selected variables. The clustering histogram curve approach highlighted eight major geomorphometric classes, separated by natural breaks, as prior terrain units (Fig. 5B). The eight classes of the geomorphometric classification, provided a more detailed overview of the geomorphological, hydrological and morphotectonic properties, relative to the study of Benito-Calvo et al. (2009), where only geomorphological characteristics were acknowledged (Table 2, Fig. 5 A and C).

ii) **Climatic classification**
The climatic zones of Crete were derived from analysis of seasonal mean temperature (1950-2000) and rainfall (1930-2000), as raster data layers (Soupios et al., 2005; Sarris et al., 2006). The climatic classification was based on the update Koppen-Geiger approach suggested by Kottek et al., (2006), using monthly temperature averages and monthly precipitation totals, as raster data layers (Köppen, 1936; Geiger, 1954) (Fig. 3). Kottek et al. (2006) identified five main global climatic types: group A, tropical/megathermal; group B, dry (arid and semiarid); group C, temperate/mesothermal; group D, continental/microthermal and; group E, polar and alpine, (Table 3). According to specific precipitation/temperature criteria, each group consists of various subcategories. Group C is the one that characterizes Crete, with subgroups varying across the island (Fig. 6).

iii) Geological classification

The geological map from IGME (1971), consisting of 74 rock formations from different geological zones, was used in the geological classification (Fig. 3). These formations were simplified to 12 main geological units, based on their rock types (sedimentary, metamorphic, volcanic) and their age (Cenozoic, Mesozoic and Paleozoic), as determined by the EMERIC project (Sarris, 2007; Fassoulas et al., 2007) (Fig. 7 and Table 4). The dominant formations in Crete are sedimentary and metamorphic rocks of Cenozoic and Mesozoic age, with only the Plattenkalk nappe being of Paleozoic age (Table 4). For each of the twelve geological units, the areal extent of the overlying geomorphometric classes was calculated (Table 4).

iv) Geodiversity classification

The spatial datasets were combined using an overlay union procedure, producing a regional geodiversity map of 229 discrete classes (Benito-Calvo et al., 2009) (Fig. 8A).
Comparison of the occurrences, for the three spatial datasets used in the geodiversity map, highlights the distribution of the dominant geomorphometric, geological and climatic classes across Crete (Fig. 8B).

v) Quantification of the geodiversity

The geometric and spatial composition of landscapes can be evaluated to quantify the geodiversity of Crete. One of the operations is diversity, a landscape property, consisting of richness and evenness (Spellerberg and Fedor, 2003). The number of classes can be defined by the compositional component of diversity, richness; while the distribution of the area of different classes can be quantified via the evenness of the diversity. Specific parameters were calculated in order to assess the geodiversity (Fig. 3 and Table 5). The quantification of landscape heterogeneity across Crete was achieved by evaluating various diversity and spatial pattern indices, using the Fragstats pattern analysis freeware (McGarigal et al., 2002). The examined indices were: Patch Richness Density (PRD), Shannon’s Diversity Index (SHDI), Simpson’s Diversity Index (SIDI), Simpson’s Evenness Index (SIEI) and Shannon’s Evenness Index (SHEI) (Table 5). Some indices (e.g. SHDI) are more sensitive to richness than evenness (Shannon and Weaver, 1949). As a result, rare patch classes disproportionately influence the weighting of the index. For instance, SIDI is less sensitive to richness and as a result it disproportionately influences the weight of the common patch classes (Simpson, 1949). Large areas can have an increased richness, due to greater heterogeneity in comparison to smaller areas.

Evenness is the observed level of diversity, divided by the maximum possible diversity for a given patch richness; it is used to determine the distribution of area among patch classes. As evenness approaches 1, the observed diversity reaches perfect evenness; conversely, larger
values imply greater landscape diversity. The set of quantitative indices were evaluated for each
district of Crete, regarding the geodiversity map and each factor individually (Table 6).

These diversity indices when combined with other spatial pattern indices can improve the
understanding of the landscape spatial composition (Benito-Calvo et al., 2009). As Crete is
characterized by a complex neotectonic status and a high degree of heterogeneity, extra spatial
pattern indices were considered in this study to examine the complex landscape spatial
composition and to quantify its shape and fragmentation characteristics. Those extra indices
were: i) shape index (SHAPE); ii) proximity index (PROX); iii) related circumscribing circle
(CIRCLE); iv) patch density (PD) and; v) perimeter-area fractal dimension (PAFRAC) (Table 5
and 6). Such characteristics can be associated with the degree of neotectonic activity influencing
an area, by highlighting any irregular, elongated and highly fragmented landscapes.

4. Results

The geomorphometric classification was based on the nine thematic maps presented in
Fig. 4. These maps were combined to derive eight geomorphometric classes (Fig. 5 and Table 2).
The following observations were made for the geomorphometric classification, relative to the
geological formations (Table 4 and Fig. 8B):

- More than half of the Quaternary (Q.al) coverage (~11% total area coverage) is found
  over coastal lands and plains (mean height: 108 m) with gentle slopes (mean: 7.8°), low
  roughness, minimal dissection and minimal landscape deformation.
The Neogene ($Mk$) formation (~29% total area coverage) is found mainly over plains and valleys with low relief, up to a mean height 371 m asl, with low roughness, minimal dissection and minimal landscape deformation.

The Tripolis Flysch zone ($ft$) is characterized by geomorphometric classes 2, 3 and 4, occurring at mean heights of 371m asl, with variable dissection and roughness.

The Pindos Flysch zone ($fo$) is characterized by similar geomorphometric classes to the Tripolis Flysch zone ($ft$) with a higher percentage found over steep hillsides and valley slopes (mean slope: $21^0$) at a mean height of 493 m asl, associated with high roughness and severe landscape deformation.

The Flysch-Schist allochthonous rocks ($f$) are rare, with their distribution characterized by geomorphometric classes 2, 3 and 4.

The Ophiolites ($o$) have a small areal extent, mainly occurring between 493-617 m asl, characterized by the geomorphometric classes 4 and 5, with a large percentage found in plateaus and plains.

The Carbonate allochthonous rocks ($K.m$) have small areal extent, mostly over low relief plains and valleys with minimal dissection.

The Carbonate Pindos rocks ($K-E$) have a small areal extent (~3% total area coverage) and are found mainly in Rethymno and Herakleio districts. This tectonic nappe formation is characterized by the geomorphometric classes 3, 4 and 6, occurring between 371-838 m asl, on gentle to steep slopes (mean: $10^0$-$22^0$), characterized by a very high degree of landscape deformation and high roughness.

The Carbonate Tripolis rocks ($K.k$) (~15% total area coverage) are distributed over most of the geomorphometric classes (classes 2 to 7); the highest percentage (~22%) is found
at a mean height of 493 m asl with steep relief (mean: 22°). This tectonic nappe formation
is characterized by a high degree of landscape deformation and roughness.

- The Phyllite-Quartzite (Ph-T) (~12% total area coverage) is characterized by low to
  intermediate relief (mean: 208-838 m asl) and by geomorphometric classes 4 and 2;
  moderate to steep slopes (mean: 17°-21°) and moderate to high roughness of hillsides and
  valley slopes.

- The Carbonate Tripali rocks (T.br) have a small areal extent (~3.6% total area coverage),
  mainly at high elevation (mean height: 838-1188 m asl) in geomorphometric classes 7
  and 6. It is characterized by steep slopes (mean: 20°-22°), with a high degree of landscape
  deformation, dissection and roughness.

- The Plattenkalk nappe (J-E) (~16% total area coverage) is distributed over intermediate
to high relief areas (mean: 493-1745 m asl), characterized by geomorphometric classes 4,
6, 7 and 8. The Plattenkalk unit is characterized by steep slopes (mean: 21°-24°), very
high dissection, high roughness and V-shaped valleys associated with severe landscape
deformation.

Crete corresponds to group C of the updated Koppen-Geiger climate classification: warm
temperate climate (sub-classes Cas, Cbs, Caf and Cbf) (Table 3). Cas type (hot and dry summer)
is the dominant climate type (Fig. 6). Cas is distributed over all the geomorphometric classes,
with a high percentage characterized by low to intermediate relief, where Q.al, Mk and K.k
formations exist, while the percentage of this climatic type decreases above ~800 m asl (Fig.
8B). The Caf type (hot summer without dry season) is distributed over all the geomorphometric
classes, but mainly characterizes the high relief mountainous blocks of Lefka Ori and Psiloritis
The Cbs type is found at mid to high altitudes (371-1188m asl) (Fig. 6), because of its climatic limits: the temperature of the hottest month is less than 22°C, but for 10 months per year the temperature remains more than 4°C (Fig. 8B).

Although the regional climatic classification approach of Kottek et al (2006) shows more details than the widely used Köppen-Geiger approach, its 0.5 degree (~50 x 50 km) spatial resolution still only characterizes the whole of Crete as having a Cas climate type. In this study a more detailed spatial resolution (0.6 x 0.6 km) of temperature and rainfall datasets was used, as determined by the EMERIC project (Sarris, 2007; Fassoulas et al., 2007). This produced a more detailed climatic classification of Crete which: revealed a wider range of climatic variation, with four climatic zones (Cas, Cbs, Caf, Cbf).

Based on the quantification of the geodiversity map, the highest PRD values were observed for Rethymno (~0.1) and Herakleio (~0.07) districts (Table 6), which have rock outcrops of relatively small areal extent and contain all the 12 geological formations. Large-area geological formations dominate Chania and Lasithi districts, which have the lowest PRD values (~0.04 and ~0.05 respectively) and contain 10 of the 12 geological formations (Table 6). Such observations are in accordance with the findings of Benito-Calvo et al. (2009), where an inverse correlation between PRD values and geological areas were observed. It indicates that PRD is not an appropriate index for the comparison of landscapes with variable areal extents, nor for evaluation of richness in complex, multi-lithology geological settings (Benito-Calvo et al., 2009).

The geodiversity of Crete was evaluated as SHDI= 4.32 or SIDI=0.976 (Table 6). For the individual districts, SHDI varies from 3.72 to 4.16 and the SIDI varies from 0.951 to 0.975 (Table 6). Crete is characterized by very high diversity values, indicating the tectonically active
status in the region. It also has the highest SHDI and SIDI values in the geological classes (Table 6), indicating high diversity and heterogeneous landscapes, due to the complex geological context across the island. Regarding the individual districts, the SHDI values are highest for Rethymno (~4.16), with Lasithi (~3.72) having the lowest value. The SIDI values are also the highest for Rethymno region, indicating the high diversity status, with the presence of all 12 geological formations. That high diversity can be linked to the active Spili fault, a normal fault that extends onshore for ~20 km and traverses the central part of Crete with a NW-SE strike (Mouslopoulou, 2011). The Herakleio district has the lowest diversity values in geomorphometric classes (Table 6), with low relief alluvial deposits and gentle slopes. In general, western Crete (Chania and Rethymno districts) has higher diversity values in the geomorphometric classes than eastern Crete (Herakleio and Lasithi districts), reflecting the higher diversity and heterogeneity of the west, which experiences most of Crete’s neotectonic activity, such as uplift and fault movement (Stiros, 1996; Shaw et al., 2008). The dominant geomorphometric classes that characterize western Crete indicate deep incised valleys, steep slopes, dissected terrain and high roughness, contrasting with the low relief alluvial deposits, gentle slopes, plains and low roughness of eastern Crete (Fig. 5 and Table 2).

Herakleio district has the lowest SHEI and SIEI values, indicating its low geomorphometric heterogeneity (Table 6). Lasithi has higher values of SHEI than Herakleio for the geodiversity map and geomorphometric classification, but the lowest SHEI values for the geological classification (Table 6). For the geological classification, Lasithi has a landscape where the distribution of area among the different geological formations becomes increasingly uneven, with J-E, K.k and Mk formations dominating. Rethymno district has the highest evenness indices values, with similar proportional relations as the respective diversity values.
Western Crete is characterized by maximum evenness, relative to eastern Crete, with the variation among the evenness indices being quite discrete (Table 6). Such variation could be linked to the extensive area of low relief plains that characterize eastern Crete, relative to the more complex heterogeneous terrain of western Crete, with its higher degree of neotectonic activity.

To quantify the landscape shape characteristics, the spatial pattern indices of SHAPE, CIRCLE and PAFRAC were calculated (Table 6). High values for SHAPE were found in Rethymno district where the patch shape becomes more irregular, due to dissected terrain with V-shaped incised valleys and steep slopes, indicating severe landscape deformation. Lower SHAPE values are observed in Lasithi district, where more regular patches correspond to lower landscape deformation and extensive low relief plains (Table 6). CIRCLE values are higher for Chania and Rethymno, with elongated landscape patches where elongation can be associated with active tectonics. High values of PAFRAC occur on the geological classes observed in western Crete, indicating the complex geodiversity of the region, with highly convoluted perimeters relative to the lower values that characterize Herakleio and Lasithi (Table 6). In the geodiversity map there are a few small variations with simple shape perimeters, highlighted by the lowest values of the index in Herakleio district (Table 6). In the geomorphometric classification, the smallest patch shape complexity is observed in Lasithi district, with higher complexity in Herakleio linked to the diverse transition from low relief plains to high relief steep mountain blocks (e.g. Psiloritis) and the southern coastline, where active faults in the Messara basin form rough terrain (Mouslopoulou, 2011) (Table 6).

To characterize landscape fragmentation, the indices of PD and PROX were evaluated (Table 6). Rethymno and Chania districts are characterized by high PD values on the
geodiversity map, indicating the complex geodiversity for western Crete. Lasithi district has very high PD values for the geological classification, which indicates a diverse geological pattern with the presence of all 12 geological formations. Herakleio district has the highest PD values regarding the geomorphometric classes, but the lowest for the terrain and geological classifications (Table 6). In this case, Herakleio district has uniform terrain and landscape patterns, from large areas of low relief plains on Cenozoic formations, contrasting with its southern coast, where most of the geomorphological classes are present in rough terrain with active faults (Mouslopoulou, 2011). Low PROX values for all classifications characterize Rethymno district, indicating high fragmentation (Table 6). Herakleio district has the highest PROX values, indicating homogenous patches which are less fragmented in distribution.

5. Discussion

This study has assessed the geodiversity of Crete by quantifying its terrain characteristics, based on geomorphological, geological and climatic information. The methodology followed the approach of Benito-Calvo et al. (2009), with a few modifications, notably:

i) the geomorphological classification consisted of various geomorphometric indices to highlight the geomorphological, hydrological and morphotectonic context;

ii) the climatic classification was based on the Kottek et al (2006) approach, but used a higher-resolution grid (0.6 x 0.6 km) which revealed a larger variation of climatic zones;

iii) the geodiversity quantification was based on a higher number of spatial pattern indices: as well as landscape evenness and diversity, we also examined fragmentation, shapes and their linkages.

The distribution of nappes across Crete is well recorded (e.g. Seidel et al., 1982; Fassoulas et al., 1994) but their geomorphological characteristics are less well known. The
geomorphometric classification derived in this study determined the geomorphological context of those geological units. Based on the topographic, permeability and rock strength characteristics of the geological units, the nappes were characterized in terms of their roughness, dissection, landscape deformation, rock resistance to erosion and steepness. The erosion-resistant nappes (J-E, T-Br Ph-T, K.k and K-E formations) form high relief regions, characterized by moderate to high roughness and dissection with V-shaped valleys, low moisture accumulation (lack of fine drainage network) and interlinkage with tectonic activity. The post-Alpine rocks, such as the weak Q.al and Mk formations, are found in low relief regions with less dissected plains and valleys, characterized by high moisture accumulation, fine drainage texture and smooth-relief landscapes that are devoid of features that indicate abrupt/tectonic deformation, such as fault scarps.

The Benito-Calvo et al. (2009) study quantified geodiversity based on diversity and evenness determinations. In this study, additional spatial pattern indices were considered for quantifying geodiversity. This has produced a better understanding of the fragmentation and shape characteristics of landscape patterns across Crete, by evaluating the degree of homogeneity or heterogeneity, the distributed fragmentation (or irregularity) of the landscape and link to neotectonic activity.

The methodology presented in this study can be useful for decision makers when evaluating a region’s geological heritage, planning the management of natural resources or designating areas for conservation, for instance. Crete is a ‘natural laboratory’ with a rich geological heritage and diverse terrain. It has a dynamic landscape with high neotectonic activity interacting with weathering and erosion to shape its terrain and landscape structure. In the context of climate change, population pressure/urbanization and degradation of natural resources,
the quantification of geodiversity - facilitated by geoinformatics - provides valuable data and maps for planners, decision-makers and policy-makers (Kostrzewski, 2011).

6. Conclusions

During the last decade the assessment of geodiversity has become a major research topic of the geoinformatic research community with landscape indices providing a powerful approach. The evaluation of geomorphometric, geological and climatic data sets can be integrated using low-cost GIS techniques, highlighting information within the interlinked geographic data. Such data integration, analysis and mapping can produce a geodiversity map which can highlight and categorize the characteristic information. The geodiversity map, along with landscape richness, evenness, fragmentation and shape irregularity, were examined via the calculated landscape indices. Those indices highlighted the correlations between the areal extent of lithologies for each district across Crete, with larger lithological units dominating Chania and Lasithi districts. The outcome showed that Rethymno district is characterized by maximum richness and evenness, while high diversity and heterogeneous landscapes characterized Chania district. Western Crete is characterized by complex geodiversity with a more irregular, elongated and fragmented landscape pattern, relative to the eastern part of the island. The overall extracted data, gives important information for quantifying geodiversity across Crete. The methodology presented provides useful information for research into landscape composition and specific geodiversity concerns, such as the aesthetic value of one landscape type over another. This can be especially useful when delineating the boundaries of national parks and other protected areas.
Acknowledgements

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References


Rowberry, M.D., 2012. A comparison of three terrain parameters that may be used to identify denudation surfaces within a GIS: a case study from Wales, United Kingdom. *Computers & Geosciences*, 43, pp 147-158.


Figures and Tables:
Fig. 1. The island of Crete, with red tones highlighting mountainous relief (LO: Lefka Ori; P: Psiloritis).
Fig. 2. The distribution of the major nappe piles formation across Crete (modified from Fassoulas, 1994 and Chatzaras, 2006).
Fig. 3. Methodological framework used to assess regional geodiversity in Crete.
Amplitude of relief ($A_r$)

Stream Length gradient ($SL$)

Stream frequency ($F_u$)

Drainage density ($D_d$)
Slope gradient ($Sg$)

Topographic Wetness Index (TWI)

Elevation relief ($Er$)

Dissection ($Di$)
Fig. 4. The thematic maps of the nine geomorphometric indices that were considered during the geomorphometric classification.
Geomorphometric classification:
Fig. 5 (A): Regional overview of the results for the ISODATA cluster algorithm for the nine selected geomorphometric indices; (B): the eight derived classes as extracted from the discriminated natural breaks of the clustering histogram curve; (C): Zoom-in map (black square in (A)) of the eight highlighted geomorphometric classes (see Table 2 for legend information).
Fig. 6. Climatic classification, based on precipitation (1930 to 2000) and temperature (1950 to 2000) datasets. The region is characterized as warm temperate climate, described by Cas, Cbs, Caf and Cbf classes.
Fig. 7. Simplified geological setting based on the classification of the 74 rock formations to 12 main units after Sarris (2007) and Fassoulas et al. (2007) studies.
Geodiversity map:
Percentages of Geomorphometric versus Geological Classes

Geological Classes:
- J.E.
- T.br.
- Ph-T.
- K.k.
- K.E.
- K.m.
- o.
- fo.
- f.
- ft.
- M.k.
- Q.al.

Geomorphometric Classes:
- Class 1
- Class 2
- Class 3
- Class 4
- Class 5
- Class 6
- Class 7
- Class 8

Percentage (%):
- 1
- 2
- 3
- 4
- 5
- 6
Fig. 8. (A) Geodiversity map, based on the union overlay procedure of the geomorphometric, geological and climatic classifications; (B) The occurrences among each of the three classifications acknowledged to the final geodiversity map.
<table>
<thead>
<tr>
<th>Layer</th>
<th>Ar</th>
<th>SL</th>
<th>Fu</th>
<th>Dd</th>
<th>Er</th>
<th>TWI</th>
<th>Sg</th>
<th>SAR</th>
<th>Di</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>1</td>
<td>0.528</td>
<td>-0.056</td>
<td>-0.138</td>
<td>0.022</td>
<td>-0.067</td>
<td>0.585</td>
<td>0.474</td>
<td>-0.048</td>
</tr>
<tr>
<td>SL</td>
<td>0.528</td>
<td>1</td>
<td>0.063</td>
<td>-0.045</td>
<td>0.015</td>
<td>-0.033</td>
<td>0.285</td>
<td>0.212</td>
<td>0.365</td>
</tr>
<tr>
<td>Fu</td>
<td>-0.056</td>
<td>0.063</td>
<td>1</td>
<td>-0.356</td>
<td>-0.002</td>
<td>0.153</td>
<td>-0.061</td>
<td>-0.032</td>
<td>0.215</td>
</tr>
<tr>
<td>Dd</td>
<td>-0.138</td>
<td>-0.045</td>
<td>0.356</td>
<td>1</td>
<td>0.004</td>
<td>0.106</td>
<td>-0.157</td>
<td>-0.092</td>
<td>0.14</td>
</tr>
<tr>
<td>Er</td>
<td>0.022</td>
<td>0.015</td>
<td>-0.002</td>
<td>0.004</td>
<td>1</td>
<td>-0.217</td>
<td>0.013</td>
<td>0.005</td>
<td>0.016</td>
</tr>
<tr>
<td>TWI</td>
<td>-0.067</td>
<td>-0.033</td>
<td>0.153</td>
<td>0.106</td>
<td>-0.217</td>
<td>1</td>
<td>-0.138</td>
<td>-0.093</td>
<td>0.088</td>
</tr>
<tr>
<td>Sg</td>
<td>0.585</td>
<td>0.285</td>
<td>-0.061</td>
<td>-0.157</td>
<td>0.013</td>
<td>-0.138</td>
<td>1</td>
<td>0.566</td>
<td>-0.307</td>
</tr>
<tr>
<td>SAR</td>
<td>0.474</td>
<td>0.212</td>
<td>-0.032</td>
<td>-0.092</td>
<td>0.005</td>
<td>-0.093</td>
<td>0.566</td>
<td>1</td>
<td>-0.133</td>
</tr>
<tr>
<td>Di</td>
<td>-0.048</td>
<td>0.365</td>
<td>0.215</td>
<td>0.14</td>
<td>0.016</td>
<td>0.088</td>
<td>-0.307</td>
<td>-0.133</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 1.** Correlation coefficient matrix table highlighting the interdependency of the input dataset layers to be used in the geomorphometric classification.
<table>
<thead>
<tr>
<th>Elevation</th>
<th>Class ID</th>
<th>Major geomorphometric units description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low relief</td>
<td>1</td>
<td>Coastal lands, alluvial deposits and plains of low height (mean: 108m asl), with gentle slopes (mean: 7.8°), fine drainage texture, low degree of landscape deformation, high moisture accumulation, low degree of dissection or vertical erosion, very low roughness.</td>
</tr>
<tr>
<td>Low relief</td>
<td>2</td>
<td>Plains and valleys with mean height 208m asl, moderate slopes (mean: 17°), very low degree of dissection or vertical erosion, permeable surface material, high infiltration capacity, moderate roughness.</td>
</tr>
<tr>
<td>Low relief</td>
<td>3</td>
<td>Hillside and slope valleys with mean height 371m asl, gentle slopes (mean: 10°), moderate degree of dissection or vertical erosion, low roughness.</td>
</tr>
<tr>
<td>Intermediate relief</td>
<td>4</td>
<td>Hillside and slope valleys with mid heights (mean: 493m asl), steep slopes (mean: 21°), coarse drainage texture, high degree of landscape deformation, low degree of dissection or vertical erosion, high roughness.</td>
</tr>
<tr>
<td>Intermediate relief</td>
<td>5</td>
<td>Intermediate plateaus and plains (mean: 617m asl), gentle slopes (mean: 11°), high moisture accumulation, low degree of landscape deformation, high degree of dissection or vertical erosion, impermeable surface material, low infiltration capacity, low roughness.</td>
</tr>
<tr>
<td>Intermediate relief</td>
<td>6</td>
<td>Hillside and slope valleys with mid to high heights (mean: 838m asl), steep slopes (mean: 22°), presence of V-shaped valleys characterized by high incision, low moisture accumulation and longitudinal ridges, moderate degree of dissection or vertical erosion, high roughness.</td>
</tr>
<tr>
<td>High relief</td>
<td>7</td>
<td>Regions with mean height 1188m asl, steep slopes (mean: 20°), high degree of landscape deformation, presence of V-shaped incised valleys, low moisture accumulation and longitudinal ridges, high degree of dissection or vertical erosion, high roughness.</td>
</tr>
</tbody>
</table>
High relief

Regions with maximum heights (mean: 1745m asl), steep slopes (mean: 24°), high degree of landscape deformation, presence of V-shaped incised valleys, low moisture accumulation and longitudinal ridges, very high degree of dissection or vertical erosion, maximum roughness.

**Table 2.** Final geomorphometric classification and description of the eight major geomorphometric classes obtained after the application of the ISODATA algorithm.

<table>
<thead>
<tr>
<th>1&lt;sup&gt;st&lt;/sup&gt;</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt;</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt;</th>
<th>Description</th>
<th>Criteria*</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>a</td>
<td>s</td>
<td>Warm temperate climate</td>
<td>Hot Summer</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>w</td>
<td></td>
<td>Warm Summer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>f</td>
<td></td>
<td>Dry Summer</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dry Winter</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Without dry season</td>
</tr>
</tbody>
</table>

**Table 3.** Updated Koppen-Geiger classification based on climate types and defining criteria (after Kottek et al., 2006). *: T<sub>hot</sub>= temperature of the hottest month; P<sub>sdry</sub>= precipitation of the driest month in summer; P<sub>wwet</sub>= precipitation of the wettest month in winter; P<sub>sdry</sub>= precipitation of the driest month in summer; P<sub>wwet</sub>= precipitation of the wettest month in winter; T<sub>mon10</sub>= number of months where the temperature is above 10°.
<table>
<thead>
<tr>
<th>Age</th>
<th>Geological units</th>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
<th>Class 4</th>
<th>Class 5</th>
<th>Class 6</th>
<th>Class 7</th>
<th>Class 8</th>
<th>Total area coverage (%) of each geological unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td>Quaternary (Q.al)</td>
<td>55.6</td>
<td>12.13</td>
<td>15.48</td>
<td>6.44</td>
<td>5.51</td>
<td>2.34</td>
<td>2.4</td>
<td>0.06</td>
<td>11.01</td>
</tr>
<tr>
<td>Cenozoic</td>
<td>Neogene (Mk)</td>
<td>38.07</td>
<td>20.84</td>
<td>26.77</td>
<td>6.88</td>
<td>4.82</td>
<td>1.51</td>
<td>1.09</td>
<td>0.0005</td>
<td>29.08</td>
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<tr>
<td>Cenozoic</td>
<td>Flysch Tripolis zone (ft)</td>
<td>3.64</td>
<td>22.15</td>
<td>24.91</td>
<td>20.59</td>
<td>11.51</td>
<td>11.23</td>
<td>5.2</td>
<td>0.76</td>
<td>3.31</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Flysch-Schist allochthonous series (f)</td>
<td>10.92</td>
<td>26.53</td>
<td>19.27</td>
<td>28.36</td>
<td>9.72</td>
<td>5.02</td>
<td>0.15</td>
<td>-</td>
<td>1.42</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Flysch Pindos zone (fo)</td>
<td>6.85</td>
<td>25.92</td>
<td>17.97</td>
<td>32.24</td>
<td>8.84</td>
<td>6.33</td>
<td>1.57</td>
<td>0.24</td>
<td>3.81</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Ophiolites allochthonous series (o)</td>
<td>7.73</td>
<td>18.48</td>
<td>14.76</td>
<td>34.37</td>
<td>20.68</td>
<td>3.37</td>
<td>0.57</td>
<td>-</td>
<td>1.13</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Carbonate allochthonous series (K.m)</td>
<td>28.53</td>
<td>42.5</td>
<td>3.71</td>
<td>2.23</td>
<td>1.2</td>
<td>1.01</td>
<td>20.81</td>
<td>-</td>
<td>0.16</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Carbonate Pindos zone (K-E)</td>
<td>2.82</td>
<td>13.92</td>
<td>19.36</td>
<td>21.52</td>
<td>4.81</td>
<td>19.9</td>
<td>13.34</td>
<td>4.3</td>
<td>3.01</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Carbonate Tripolis zone (K.k)</td>
<td>7.48</td>
<td>16.04</td>
<td>10.42</td>
<td>21.6</td>
<td>11.64</td>
<td>12.16</td>
<td>14.9</td>
<td>5.73</td>
<td>15.1</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Phyllite-Quartzite series (Ph-T)</td>
<td>7.84</td>
<td>23.39</td>
<td>11.28</td>
<td>32.29</td>
<td>8.39</td>
<td>14.13</td>
<td>2.6</td>
<td>0.04</td>
<td>12.15</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Carbonate Tripali zone (T-Br)</td>
<td>11.32</td>
<td>13.4</td>
<td>12.01</td>
<td>14.96</td>
<td>6.75</td>
<td>17.48</td>
<td>20.21</td>
<td>3.84</td>
<td>3.61</td>
</tr>
<tr>
<td>Palaeozoic</td>
<td>Plattenkalk nappe (J-E)</td>
<td>3.8</td>
<td>10.24</td>
<td>6.4</td>
<td>17.37</td>
<td>5.99</td>
<td>17.52</td>
<td>21.34</td>
<td>17.31</td>
<td>16.21</td>
</tr>
</tbody>
</table>

Table 4. The geomorphometric classes areal distribution over each of the twelve geological units and the total area coverage (%) of each geological unit across Crete.
<table>
<thead>
<tr>
<th>Landscape metric</th>
<th>Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Patch Richness Density (PRD)</strong></td>
<td>PRD &gt;0, without limit</td>
<td>PRD equals the number of different patch classes present within the landscape boundary, divided by total landscape area (m²), multiplied by 10000 and 100 (to convert to 100 hectares). It standardizes richness to a per area basis that facilitates comparison of landscapes.</td>
</tr>
<tr>
<td><strong>Shannon’s Diversity Index (SHDI)</strong></td>
<td>SHDI ≥0, without limit</td>
<td>SHDI equals the sum, across all patch classes, of the proportional abundance of each patch class multiplied by that proportion. It increases as the number of different patch classes increases and the proportional distribution of area among patch classes becomes more equitable.</td>
</tr>
<tr>
<td><strong>Simpson’s Diversity Index (SIDI)</strong></td>
<td>0 ≤ SIDI ≤ 1, SIDI = 0, when the landscape contains only one patch (no diversity)</td>
<td>SIDI equals the sum, across all patch classes, of the proportional abundance of each patch class squared. It increases as the number of different patch classes increases and the proportional distribution of area among patch classes becomes more equitable. Represents the probability that any two pixels selected at random would be different patch classes.</td>
</tr>
<tr>
<td><strong>Shannon’s Evenness Index (SHEI)</strong></td>
<td>0 ≤ SHEI ≤ 1, SHEI = 0, when the landscape contains only one patch (no diversity), while approaches 0 as the distribution of area among the different patch classes becomes increasingly uneven; SHEI = 1, when distribution of area among patch classes is perfectly even (proportional abundances are the same)</td>
<td>SHEI equals the sum, across all patch classes, of the proportional abundance of each patch type multiplied by that proportion, divided by the logarithm of the number of patch classes. It is expressed such that an even distribution of area among patch classes results in maximum evenness. Evenness is the compliment of dominance.</td>
</tr>
<tr>
<td><strong>Simpson’s Evenness Index (SIEI)</strong></td>
<td>0 ≤ SIEI ≤ 1, SIEI = 0, when the landscape contains only one patch (no diversity), it approaches 0 as the distribution of area among the different patch classes becomes increasingly uneven; SIEI = 1, when distribution of area among patch classes is perfectly even</td>
<td>SIEI equals the sum, across all patch classes, of the proportional abundance of each patch type squared, divided by 1 minus 1, divided by the number of patch classes. It is expressed such that an even distribution of area among patch classes results in maximum evenness. Evenness is the compliment of dominance.</td>
</tr>
<tr>
<td><strong>Shape index (SHAPE)</strong></td>
<td>SHAPE ≥ 1, without limit. SHAPE = 1 when the patch is square and increases without limit as patch shape becomes more irregular.</td>
<td>Equals patch perimeter (m) divided by the square root of patch area (m²), adjusted by a constant to adjust for a square standard.</td>
</tr>
<tr>
<td><strong>Proximity index (PROX)</strong></td>
<td>PROX ≥ 0, PROX = 0, if a patch has no neighbors of the same patch type within the specified search radius. PROX increases as the neighborhood (defined by the specified search radius) is increasingly occupied by patches of the same type and as those patches become closer and more contiguous (or less fragmented) in distribution. The upper limit of PROX is affected by the search radius and the minimum distance between patches.</td>
<td>Equals the sum of patch area (m²) divided by the nearest edge-to-edge distance squared (m²) between the patch and the focal patch of all patches of the corresponding patch type whose edges are within a specified distance (m) of the focal patch. Note, when the search buffer extends beyond the landscape boundary, only patches contained within the landscape are considered in the computations. In addition, note that the edge-to-edge distances are from cell center to cell center.</td>
</tr>
<tr>
<td><strong>Related circumscribing</strong></td>
<td>0 ≤ CIRCLE ≤ 1, CIRCLE approaches 0 for circular patches and approaches 1 for the smallest circumscribing circle.</td>
<td>Equals 1 minus patch area (m²) divided by the area (m²) of the smallest circumscribing circle.</td>
</tr>
<tr>
<td><strong>circle (CIRCLE)</strong></td>
<td>elongated linear patches.</td>
<td>854</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------</td>
<td>-----</td>
</tr>
<tr>
<td><strong>Perimeter-area fractal dimension (PAFRAC)</strong></td>
<td>1 $\leq$ PAFRAC $\leq$ 2. A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a Euclidean geometry (i.e., an increase in patch shape complexity). PAFRAC approaches 1 for shapes with very simple perimeters such as squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters.</td>
<td>855</td>
</tr>
<tr>
<td><strong>Patch density (PD)</strong></td>
<td>$PD &gt; 0$, constrained by cell size. $PD$ is ultimately constrained by the grain size of the raster image, because the maximum $PD$ is attained when every cell is a separate patch. It expresses number of patches on a per unit area basis that facilitates comparisons among landscapes of varying size.</td>
<td>857</td>
</tr>
</tbody>
</table>

Table 5. Landscape metrics with descriptive details of each index.
### Table 6

<table>
<thead>
<tr>
<th>(a)</th>
<th>Area (km²)</th>
<th>Landscape and patch metrics (Geodiversity map)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PRD</td>
<td>SHDI</td>
</tr>
<tr>
<td>Crete</td>
<td>8336</td>
<td>0.027</td>
</tr>
<tr>
<td>Chania</td>
<td>2376</td>
<td>0.045</td>
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<tr>
<td>Rethymno</td>
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<td>0.099</td>
</tr>
<tr>
<td>Herakleio</td>
<td>2641</td>
<td>0.075</td>
</tr>
<tr>
<td>Lasithi</td>
<td>1823</td>
<td>0.059</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(b)</th>
<th>Area (km²)</th>
<th>Landscape and patch metrics (Geomorphometric classification)</th>
</tr>
</thead>
<tbody>
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<td>SHDI</td>
</tr>
<tr>
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<td>0.01</td>
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<tr>
<td>Chania</td>
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<td>0.006</td>
</tr>
<tr>
<td>Herakleio</td>
<td>2641</td>
<td>0.003</td>
</tr>
<tr>
<td>Lasithi</td>
<td>1823</td>
<td>0.004</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(c)</th>
<th>Area (km²)</th>
<th>Landscape and patch metrics (Geological classification)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>SHDI</td>
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<tr>
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<td>Chania</td>
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<tr>
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<td>0.004</td>
</tr>
<tr>
<td>Lasithi</td>
<td>1823</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 6. a) Landscape and patch metrics for Crete and the individual districts of Crete, based on the geodiversity map of the island; b) landscape and patch metrics for Crete and the individual districts of Crete, based on the geomorphometric classification of the island; c) landscape and patch metrics for Crete and the individual districts of Crete, based on the geological classification of the island.