High-Resolution Spatial Data Analysis for Monitoring Urban Sprawl in Coastal Zones: A Case Study in Crete Island

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Abstract. Urban sprawl heavily affects coastal areas worldwide, posing threats to the environment and resulting in unsustainable urban growth patterns. This is particularly true in the Mediterranean Region, where coastal and especially insular territories constitute distinct cases of fragile ecosystems, affected by long-lasting mass tourism development trends. This research proposes a methodology for monitoring urban sprawl in coastal areas. High-resolution data for built-up areas are used in this respect, provided by the Global Human Settlement Layer (GHSL). Spatial data are processed using GIS technology; and FRAGSTATS software is used to calculate spatial metrics that quantify density, clustering, geometrical complexity and dispersion of the built environment. The proposed methodology is applied to a case study in Crete, a remarkable example of Mediterranean island community, heavily affected by mass tourism development. Urban growth trends in the period 1975–2014 are explored in this respect; and urban sprawl patterns are analyzed at a disaggregated level along the northern coastal zone, using recent GHSL data based on Sentinel-2 images (period 2017–2018). Using a combination of principal component analysis and cluster analysis, different typologies are identified and zones mostly affected by urban sprawl are highlighted.

Keywords: Coastal zones · Urban sprawl · Spatial data · Spatial metrics · GIS · Mediterranean Region · Crete Island

1 Introduction

Coastal zones, i.e. the interface between the mainland and the sea, are places of remarkable natural and cultural richness and diversity, particularly vulnerable to natural and human pressures, which provide a wide variety of ecosystems' services [1]. Within these zones, a multitude of social, economic and environmental processes occur. Socio-economic processes in coastal zones, however, usually result in *spatial conflicts* and pose *pressure* on the natural (land and maritime) and human ecosystems.

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Coastal zones in the *Mediterranean Region* in particular, being important areas for human habitation and a range of economic activities through centuries, constitute exemplary cases of heavily affected territories in terms of urbanization processes that can be hardly assimilated by the coastal ecosystems. These processes are fueled by, among others, a *mass tourism development pattern*, which goes beyond capacity limits and threatens the sustainable use of coastal, land and maritime, resources. Deployment of infrastructure, artificial land expansion and the accelerated dispersion of built-up areas are key drivers of coastal urban sprawl processes, consuming vast amounts of land and placing relevant ecosystems at stake. As a result, urban sprawl in coastal areas has been recognized as an *unsustainable model of growth* [2], leading to biodiversity loss, pollution of soil and water deposits, overexploitation of natural land and maritime resources as well as land degradation, to name a few. In the European context, this pressure is expected to grow, taking into consideration the European strategy [3] for further exploiting coastal and maritime tourism opportunities, offered by the extraordinary naturally- and culturally-wealth and the great diversity of coastal regions. Coastal and maritime tourism is regarded as a major source of growth and jobs' creation, being listed as one of the five focus areas in the EU blue economy [4].

Islands provide a natural testing ground of urban spatial expansion within limited area [5]. Urban sprawl is a critical issue in coastal zones in Mediterranean island territories, perceived as distinct cases of fragile and vulnerable ecosystems, in many cases presenting a high degree of artificialization [6]. In such zones, disordered standalone urbanization and infrastructure development or combined with uncoordinated industrial, tourism-related, fishing and agricultural activities, guides currently the rapid degradation of coastal habitats/resources. *Vulnerability* of coastal ecosystems in general and *insular coastal ecosystems* in particular is predominantly attributed to their high environmental value, natural sites protected by international and European laws such as Natura 2000 network, including Sites of Community Importance (SCI), Special Protection Areas (SPA) etc. Coupled with the confined space, insular coastal zones usually dispose a rather limited *carrying capacity* [7]. Thus, a saturation point of coastal zones can be quickly reached, considering also that island territories constitute popular, mostly mass, leading tourism destinations, demonstrating summer peaks of tourist arrivals. Human activities, e.g. urbanization and tourism, have already a strong impact on many island coastal areas, while the state of these areas is expected to further deteriorate under the severe risks of Climate Change and environmental degradation [8], calling thus for urgent action. In doing so, the need to develop methodologies as well as increase technical capabilities and scientific knowledge for analyzing and monitoring *urban sprawl in coastal areas* and support more informed national and regional policies to unfold, becomes urgent.

Coastal urban sprawl is a *dynamic process*, and addressing its spatial and temporal dynamics is crucial for assessing the pressure on respective zones. To this end, detailed information is required for dealing with sustainable land management. However, a major drawback until recently was the lack of *high-resolution spatial data*, rendering the analysis and monitoring of urban sprawl in coastal zones a difficult task. As a result, comparative studies dealing with urban sprawl processes in coastal Mediterranean areas are sparse [9–12]; and are in most cases based on Corine Land Cover (CLC) data [13–16].

CLC data, however, while valuable in the exploration of land cover changes in agricultural and natural land cover categories, seems rather inappropriate for the analysis of urban sprawl in coastal zones due to the crude spatial resolution with the Minimum Mapping Unit (MMU) set to 25 ha. Additionally, since a large proportion of built-up areas are scattered within agricultural and semi-natural or natural areas, CLC data cannot really capture spatially-detailed processes of urban expansion.

Recently, a new generation of *high-resolution spatial data* has been developed, with the involvement of the European Environment Agency (EEA), the Copernicus Land Monitoring Service (CLMS), the Joint Research Center, etc. Based on the above advances and spatial data availability, the *focus* of the present work is on developing a methodology and using recent high-resolution data, specifically multi-temporal data for built-up areas, provided by the Global Human Settlement Layer (GHSL) [17], for indulging in the study of coastal urban sprawl phenomenon. More specifically, spatial data and spatial metrics are used to analyze patterns of coastal urban sprawl in Crete Island (Greece). In this respect, spatial metrics that quantify density, clustering, geometrical complexity and dispersion of the built environment, are explored at a disaggregated level. A new methodological framework is developed, involving the estimation of spatial metrics at a disaggregated/local level (tile analysis) combined by principal component analysis and cluster analysis. This is important, since urban sprawl usually results into complex and spatially differentiated patterns and by using high-resolution data typologies of urban sprawl can be accurately identified. Methodology is applied to a case study in Crete, a remarkable example of Mediterranean island, heavily burdened by mass tourism development. Research results provide a detailed mapping of urban sprawl patterns along the northern coastal zone, in order to support more informed planning and decision-making processes towards a currying capacity-oriented and sustainable coastal zone management.

The structure of the paper has as follows: in Sect. 2 the data and methodology are presented; in Sect. 3 the case study area is sketched and temporal growth trends are discussed; Sect. 4 includes the spatial metrics' estimation and the identification of different typologies; while finally Sect. 5 summarizes key conclusions of this research work.

2 Data and Methodology

Assessment of urban sprawl in the case study example of this work – Crete Island – is based on the GHSL *multi-temporal data* for built-up areas, processed by *Geospatial tools* and *GIS procedures* for quantifying built-up area expansion in the coastal zone. Multitemporal data for the period 1975–2014 are used to explore current trends; while high-resolution data (10m resolution), based on Sentinel-2 images for the period 2017–2018 (GHS-BUILT-S2), are used to analyze the structural and morphological attributes of urban sprawl patterns. *Spatial metrics* used in the proposed methodology can be defined as indicators, obtained from the analysis of thematic-categorical maps, which bring out the spatial component of the urban form and the dynamics of change and growth processes [18]. Estimations refer to the level of patches, defined as discrete areas that appear to be homogenous with respect to some characteristic, such as land use, habitat

type, etc. Various examples of spatial metrics' application in urban landscape pattern analysis can be found in the literature [19–22].

The proposed methodology is applied to an island territory, namely Crete, a remarkable example of Mediterranean island, heavily burdened by mass tourism development. *Coastal urban sprawl patterns* are analyzed at a disaggregated level along the northern coastal zone, using recent GHSL data (period 2017–2018).

2.1 High-Resolution Spatial Data for Built-Up Areas

Recently, the availability of new sensors triggered the proliferation of moderate to high resolution (30–50 m) long time-series global datasets of human settlements [17]. As *high-resolution open spatial data* become available, enchased methodologies for the analysis and monitoring of urban sprawl in coastal zones can be developed. In this study, the following GHSL high-resolution data for built-up areas are used:

- GHS-BUILT: Multi-temporal classification of built-up presence as derived from Landsat image collections (1975, 1990, 2000, 2014) at 30 m spatial resolution. 7 categories are defined, namely 0 = no data, 1 = water surface, 2 = land no built-up in any epoch, 3 = built-up from 2000 to 2014 epochs, 4 = built-up from 1990 to 2000 epochs, 5 = built-up from 1975 to 1990 epochs, 6 = built-up up to 1975 epoch. Dataset is delivered as (8bit) VRT files, projected in the Pseudo Mercator (EPSG: 3857).
- GHS-BUILT-S2 R2020A: GHS built-up grid, derived from Sentinel-2 global image composite for reference year 2018, using Convolutional Neural Networks [18]. This dataset corresponds to a global map of built-up areas, expressed in terms of a probability grid at 10m spatial resolution. Built-up probability values are rescaled in the range 0–100 (0 for probability = 0 and 100 for probability = 1). Dataset is delivered as tiff raster files, while each tile inherits the projection of the UTM grid zone to which it belongs to.

To analyze trends of urban growth in the period 1975–2014 in the case study area, a density-gradient analysis was used, based on buffer zones from the coast. GHS-BUILT data were processed using the "Tabulate area" tool, provided in the ArcGIS Spatial Analyst. To analyze the built-up patterns for the period 2017–2018, GHS-BUILT-S2 R2020A data were used. A binary version of the raster was constructed by setting a threshold point to binarize the probabilistic output (built-up probability values) [23]. A cell is defined as "built-up" if raster value >20, while otherwise is defined as "non built-up".

2.2 Spatial Metrics

Spatial metrics are patch-based indicators that bring out the spatial component of the urban form and the dynamics of change and growth processes [18]. Such metrics have been developed under the framework of landscape ecology [24] for assessing density, geometry (shape) and dispersion of patches. Area/density/edge metrics, shape metrics, proximity metrics, contagion/diversity metrics, connectivity metrics, are usually distinguished. FRAGSTATS software [25], a public domain software (current version 4.2), is

used to calculate a long list of spatial metrics. In this study, urban patches are defined as discrete built-up areas that are identified based on a binary raster grid. At this stage, only one class is defined, i.e. urban patches, representing built-up areas and featuring a developed/non-developed land dichotomy approach. The *spatial metrics* used in this study are:

- COV: the sum of the areas (in ha) of all patches expressed as percentage (%) of total landscape area.
- PD: Patch Density, estimated as the number of patches divided by the total landscape area.
- ED: Edge Density, estimated as total length (m) of patch edges, divided by total landscape area.
- MPS: Mean Patch Size, estimated as the mean area of patches.
- LPI: Largest Patch Index, estimated as the area of the largest patch divided by the total landscape area.
- SHAPE: An indicator that compares the actual perimeter of a patch to the minimum perimeter in the theoretical case of a simple geometrical shape.
- GYRATE: The mean distance (m) between each cell in the patch and the patch centroid. Gyrate is higher for large irregular/elongated patches.
- ENN: The mean Euclidean distance to the nearest neighboring patch, calculated as the shortest edge-to-edge distance.
- CONNECT: A measure of connection between patches, divided by the total number of possible connections among them. In this study, threshold distance is set to 100 m.
- PROX: A measure of proximity, estimated as the sum of patch area (m^2) divided by the nearest edge-to-edge distance squared (m^2) between the patch and the focal patch of all patches within a threshold distance (in this study set to 500 m) of the focal patch.

GHS-BUILT data are processed in *ArcGIS*, reclassified and exported as GeoTIFF grids that are used as input files in FRAGSTATS software. Uniform tiles with a side-length of 1 km are used to calculate spatial metrics at a spatially disaggregated/local level. FRAGSTATS results are exported as CSV (Comma-separated values) files; and are mapped in ArcGIS, by joining the raster file containing the tiles to the CSV file, based on a unique Tile_id Field. At a next step, and by using SPSS Statistics software, *Principal Component Analysis* (PCA) is used to combine the spatial metrics and reduce their number to a minimum set of explanatory factors. *Cluster analysis* is then applied, to explore different built environment typologies. PCA and cluster analysis have been widely used in urban morphology research [14, 26]. Using this method in the case study of Crete Island, zones mostly affected by urban sprawl can be identified, along the over 500 km coastline of the northern coastal zone.

3 Crete Island Case Study

3.1 Current State of the Study Region

Crete Island is marked by a multitude of cultural, historical and natural sites of great and supra-local importance. 53 Natura 2000 areas are hosted in this island, covering

3,710 square km (45% of total island area), along with 57 wildlife repositories and many important archaeological sites. Geomorphology is rough, with mountainous areas covering mainly the central and southern part, restraining urban development along the northern coast, where land is relatively flat. Crete has mild climate conditions, characterized as temperate to maritime in plain areas and mountainous in areas of higher elevation [27]. Major cities of the northern coast are Heraklion, Chania, Rethymno and Agios Nikolaos, while the town of Ierapetra is located in the southeast (Fig. 1). Total population is 591,772 inhabitants (Census 2011), increasing by 10% in the period 1991–2011, with most coastal communities gaining population, while inland communities displaying population decline trends. Agricultural land covers about 44% of total area, marginally increasing during the past decades. Olive groves cover 25.9% of the island, with olive oil being a main product of the primary sector. Forests cover only 3.5% of the island; however, transitional natural areas (mainly Natural grasslands and Sclerophyllous vegetation) cover a total of 45% and are decreasing by 21,000 ha since 1990. According to CLC data, artificial areas increased from 1.3% of total island area to 2.2% in 1990–2018. Discontinuous urban fabric, industrial/commercial areas as well as sport and leisure facilities are the most fast-growing land use categories in Cretan island.

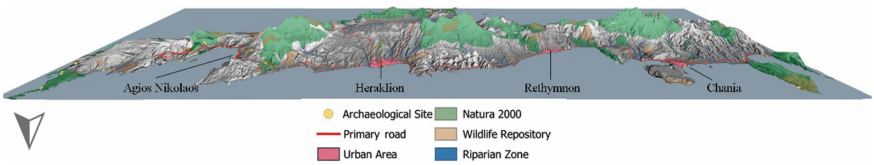

Fig. 1. 3D view of Crete Island (northern coast), Source: Own elaboration

Crete is among the Greek islands where tourism has been developed in a very massive way since the 80's; and has been growing significantly since then, attracting yearly about 2 million foreign visitors [27]. Based on the mild climate conditions and the rich combination of natural and cultural attributes, tourist potential is high, with the tourism period spanning from April to October. Tourism facilities include 1,619 hotels with 96,367 bedrooms and a total of over 187,600 beds (in 2019). Airbnb platform has currently 18,000 registered rooms and houses/apartments, mostly concentrated along the northern coast and close to the major urban centers (Fig. 2). Direct employment in the tourism sector (hotels and restaurants) increased from 8% of total employment in 1991 to 15% in 2011. However, tourism-related employment also affects the constantly growing tertiary sector that contributes over 65% of total employment in Crete (Census 2011). During the period 1991–2011, employment in the primary sector was reduced from 30% to 13%, while remained relatively stable in the secondary sector (from 17% to 15% in the same period).

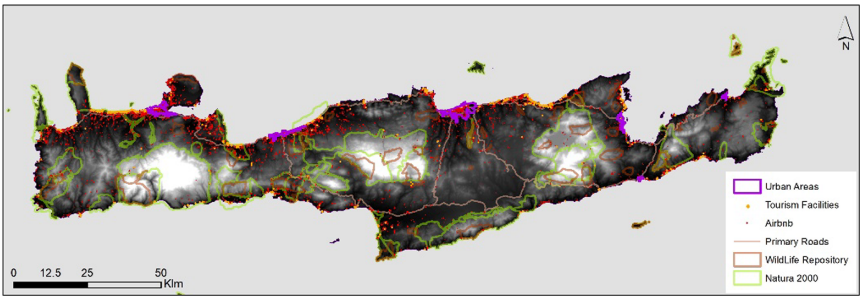

Fig. 2. Tourism facilities and Airbnb dispersion in Crete, Source: Own elaboration on Data from OpenStreetMap and InsideAirbnb Platform

In Crete, a *polarized pattern* of development is observed. The northern coast is actually overcrowded, hosting almost all major urban centers (except for Ierapetra), the major transportation infrastructure – VOAK highway (North Road Axis of Crete) –, the two major airports in Heraklion and Chania, and the major ports connecting Crete to mainland Greece. It also hosts the majority of tourism infrastructure, being the outcome of the domination of the 3S (Sea-Sun-Sand) mass tourism model since the '80s, with major tourism investments along the easily accessible sandy beaches of the northern coast. Furthermore, as a result of the mountainous geomorphology and inadequate transport infrastructure, the southern part of the island remains largely intact. In the northern coast, many areas have already exceeded own Tourism Carrying Capacity, a critical issue that needs to be addressed; while this part is confronted with environmental pressures due to coastal erosion threatening the coastline and, consequently, the current pattern of tourism development [28].

3.2 Coastal Urban Sprawl in the Island of Crete

Urban land expansion in Crete Island has been intense during the past decades, encroaching in a spontaneous and non-organized way, mainly along the northern coast. According to GHS multitemporal data elaboration, it is inferred that urban land has expanded by 23% as a total in Crete Island, corresponding to 4,120 ha of new built-up areas in the period 1975–2014. Rates of urban growth are higher in the Chania and Rethymno Prefectures (25% and 72% respectively); while in Heraklion Prefecture urban growth rate is estimated to 15% and in Lasithi Prefecture to 20%. The density gradient (Fig. 3) is flattened beyond a distance of 5th km from the coast, while in the immediate coastal zone (0–1 km) built-up areas are maximized. Therefore, the crucial coastal zone is perceived up to 5 km from the coast, followed by a hinterland zone. The 5 km coastal zone was used as the spatial basis for estimating spatial metrics at a disaggregated/local level. Distinctive examples of coastal areas, developed as resort towns in a sprawling way, are presented in Fig. 4.

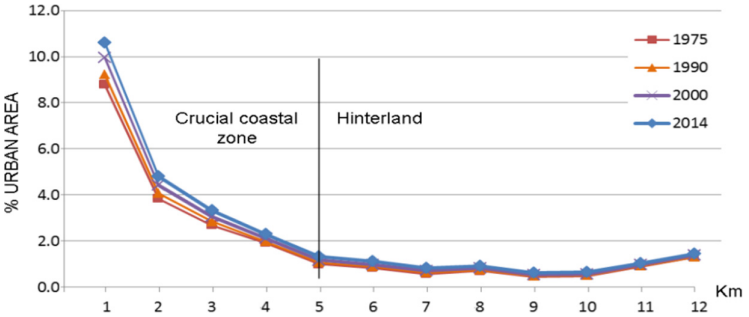

Fig. 3. Density gradient of built-up/urban areas along distance from the northern coast, Source: Own elaboration



Fig. 4. Coastal development in the mass tourism resort areas of Hersonissos (up) and Platanias (down) (left side: 1945 aerophoto, obtained from http://gis.ktimanet.gr/ - right side: Google Earth 2020), Source: Own elaboration

4 Results

Based on the GHS-BUILT-S2 R2020A data for 2017–2018, the set of spatial metrics described in Sect. 2.2 was estimated in order for urban sprawl typologies in the study area to be analyzed. Patches were defined as "built-up areas", using a probability threshold equal to 20. Using a reclassification tool, all other areas in the analysis (non-built-up agricultural and natural land) were identified as "Background". The final dataset was masked, based on the 5 km zone along the northern coast, and rasterized at a spatial resolution of 10 m. Using the FRAGSTATS software, uniform tiles of 1X1km were applied, while a border rule was used so that only tiles with a maximum of 75% border/no data pixels to be processed. This choice was made in order to avoid estimations for tiles

mainly outside the case study area or covered by sea. Based on these settings, 1469 valid tiles (with a least one patch inside) were processed, and spatial metrics were estimated at this disaggregated level. Maps showing the spatial distribution of selected metrics are presented in Fig. 5.

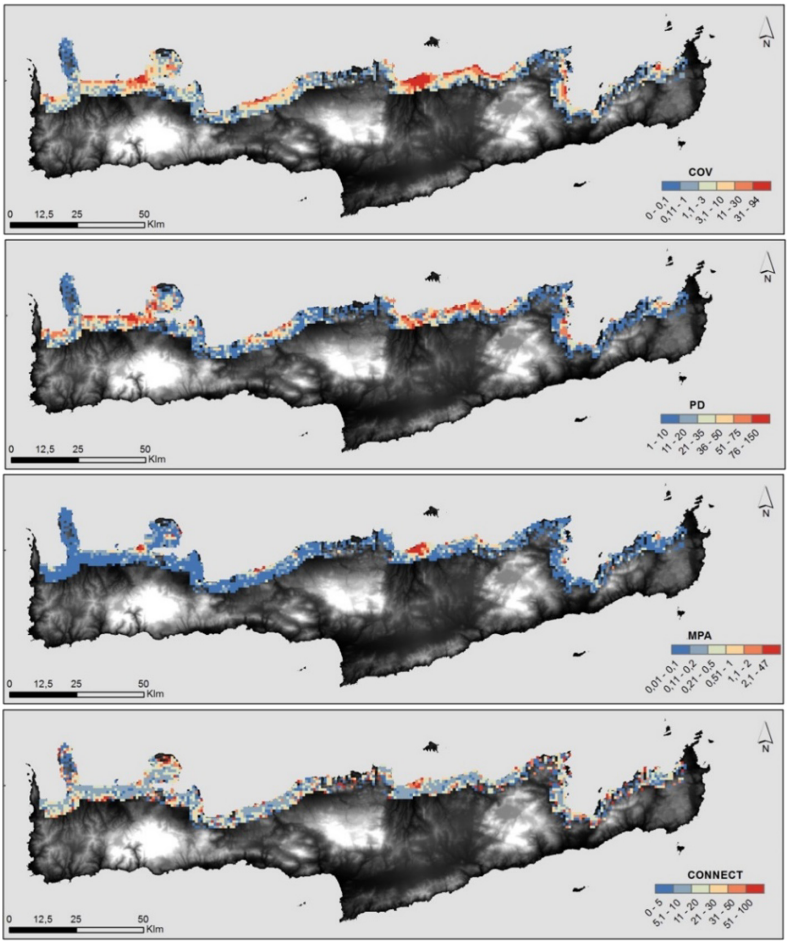

Fig. 5. Maps of selected metrics, distribution of values along the 1 km tiles, Source: Own elaboration.

Results demonstrate considerable differences in the spatial distribution of built-up areas along the northern coastal zone of Crete. COV ranges from 0 to 94, with a mean value of 5.7 and a standard deviation 12.4. High COV values in the range 31–94 are concentrated close to core urban areas, while COV values in the range 11–30 are associated with periurban cells and a few cells with intense tourism development. Most COV values are lower than 10, indicating very low density development along the coastal zone. COV

is highly correlated to LPI (Pearson's correlation 0.95). This result is expected, since in very densely built-up cells a large continuous urban patch is usually formed.

PD ranges from 1 to 153, with a mean value of 23.9 and a standard deviation 24.3. High PD values (>50) spread are noticed in many parts of the northern coast, mainly around the major urban centers, but also in areas with immediate accessibility to the sea, e.g. Platanias-Colimbari zone in the west of Chania city and the Hersonissos-Malia area in the east of Heraklion city. Low PD values are observed towards the hinterland and in areas affected by tourism development to a lesser degree. ED is highly correlated to PD (Pearson's correlation 0.81) and ranges from 0.4 to 437, with a mean value of 51.5 and a standard deviation 72.2. MPS is an important metric as it directly measures the size of patches and the degree to which urban land is aggregated into larger clusters. MPS ranges from 0.1 to 46.9, with a mean value of 0.3 and a standard deviation of 11. In 97% of the tiles, MPS values are less than 1ha. This fact shows that development along the coast is patchy and discontinuous. MPS is correlated to: LPI (Pearson's correlation 0.66), PROX (Pearson's correlation 0.7) and GYRATE (Pearson's correlation 0.87), as those metrics are affected by the size of patches.

LSI ranges from 1 to 15.8, with a mean value of 4.8 and a standard deviation of 3. LSI is considered a good metric of urban sprawl, since it accounts for shape complexity and is maximized in complex, irregular patches of urban land. LSI is high (>5) in the largest part of the coastal zone, also presenting very high values in periurban areas. LSI metric is highly correlated to PD and ED (Pearson's correlation 0.9 and 0.79 respectively). GYRATE is higher for large irregular/elongated patches and ranges from 5 to 195, with a mean value of 12.4 and a standard deviation of 11.3. Values between 10 and 25 cover most parts of the northern coast, around major urban centers and tourism development zones as well as around a few inland settlements.

PROX ranges from 0 to 1506, with a mean value of 23.1 and a standard deviation 120. PROX is by definition affected by patch area, therefore it is highly correlated with COV, LPI and MPS, presenting high values (>50) close to urban centers and tourism development zones. ENN ranges from 0 to 1021, with a mean value of 92.9 and a standard deviation 123.5. ENN values are in most coastal tiles smaller than 100 m; while, with reference to the hinterland values, these fall into a range of 100–500 m. CONNECT ranges from 0 to 100 with a mean value of 16.4 and a standard deviation of 20.6. Connectivity of built-up areas at the local level (100 m) is higher in urban centers and in compactly built-up agricultural settlements far from the coast. On the other hand, in almost all tiles located up to 2 km from the coast, connectivity is very low (<20).

As many metrics are correlated, a PCA analysis was used to reduce the variables to a minimum set of factors. This will also ensure that collinearity is avoided, and synthetic indicators taking into account the main characteristics of the initial spatial metrics can be obtained. Varimax rotation with Kaiser Normalization has been used, while the KMO index (Kaiser–Meyer–Olkin) and communalities were estimated. A total of 3 factors were obtained (Table 1), with eigenvalues >1, accounting for 83.5% of the total variance of the initial variables. The indexes used for an evaluation of the PCA analysis show a good performance. KMO was estimated equal to 0.739, while communalities passed the test of 0.5 (all communalities >0.70). Bartlett's test of sphericity presents a small value of significance level (less than 0.05), therefore the hypothesis that correlation matrix is

an identity matrix is rejected. In Factor 1 (F1) the COV, MPA, LPI, PROX, GYRATE metrics are loaded, in Factor 2 (F2) the LSI, PD, ED metrics and in Factor 3 (F3) the CONNECT and ENN metrics. F1 corresponds to Coverage and Aggregation of built-up areas, F2 to Patch/Edge Density, and F3 to Connectivity & Dispersion.

Table 1. PCA results (Rotated Component Matrix)

Metrics	Factors		
	F1	F2	F3
LPI	0.927	0.213	
PROX	0.910		
GYRATE	0.880		0.159
MPA	0.859	−0.114	0.122
COV	0.856	0.442	
LSI	0.107	0.945	
PD		0.939	
ED	0.463	0.826	
CONNECT	0.194	−0.324	0.753
ENN		−0.427	−0.735

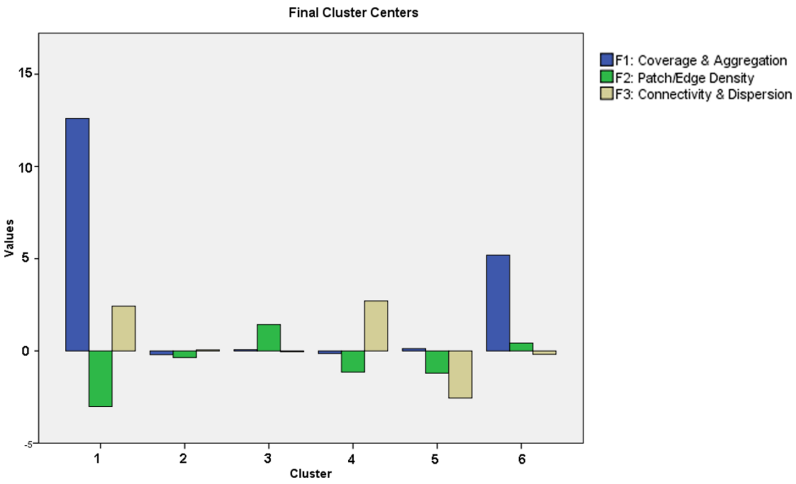

Fig. 6. Final cluster centers, Source: Own elaboration.

Using the PCA factors, *Cluster Analysis* was performed by the K-means method. Based on the Scree plot that shows the increase in homogeneity within each cluster with respect to the increase in the number of clusters, 6 clusters were selected as an optimal choice, since the slope of the curve is flattened at this point. Final cluster centers are

presented in Fig. 6 and summary stats (mean values and standard deviation) for the spatial metrics per cluster are tabulated in Table 2. Typical built-up patterns per cluster are mapped in Fig. 7.

Table 2. Summary statistics for spatial metrics per cluster

Cluster		COV	PD	ED	MPS	LPI	LSI	GYRATE	ENN	PROX	CONNECT
1 N = 4	Mean	**90.2**	**2.3**	**159**	**41.6**	**90.2**	**4.2**	**176.6**	**21**	**1157**	**91.7**
	Std. D.	4.9	0.5	61.2	9.4	5.0	1.8	32.2	1,2	190	16.7
2 N = 911	Mean	**1.4**	**13.7**	**19**	**0.1**	**0.6**	**3.6**	**10.3**	**81**	**2.5**	**14.5**
	Std. D.	2.2	10.5	18.1	0.2	1.7	1.7	5.3	59	7.5	11.9
3 N = 369	Mean	**13.9**	**58.9**	**140**	**0.3**	**6.6**	**9.0**	**14.9**	**40**	**30.3**	**8.9**
	Std. D.	11.7	20.1	76.9	0.3	9.6	1.9	4.8	9	56.4	4.6
4 N = 72	Mean	**0.6**	**4.2**	**6.8**	**0.1**	**0.5**	**2.1**	**12.0**	**41**	**3.0**	**89.8**
	Std. D.	0.9	2.3	6.6	0.2	0.9	0.6	7.1	18	6.4	16.8
5 N = 92	Mean	**0.2**	**3.0**	**2.8**	**0.1**	**0.1**	**1.7**	**8.4**	**480**	**0.0**	**0.6**
	Std. D.	0.2	1.4	1.9	0.1	0.2	0.3	3.9	206	0.0	2.7
6 N = 21	Mean	**73.1**	**14.4**	**247**	**6.2**	**70.5**	**6.5**	**48.0**	**27**	**741**	**32.6**
	Std. D.	9.2	7.5	66.5	2.6	11.7	2.3	15.3	6	409	12.6
Total N = 1469	Mean	**5.7**	**23.9**	**51.5**	**0.3**	**3.3**	**4.8**	**12.4**	**930**	**23.1**	**16.4**
	Std. D.	12.4	24.3	72.2	2.3	11.0	3.0	11.3	1235	120.0	20.6

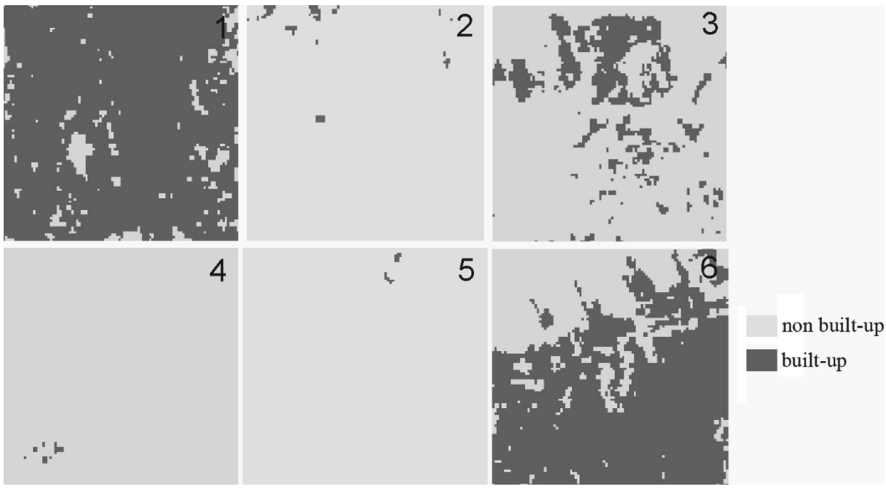

Fig. 7. Typical built-up patterns (per cluster), Source: Own elaboration.

The spatial distribution of clusters is presented in Fig. 8. Based on the spatial metrics estimated, Cluster 3 is considered as the main typology related to intense urban sprawl. Cluster 3 contains 359 tiles, located mainly in the immediate coastal zone and also concentrated in periurban zones around compactly built-up urban core areas. In Cluster 3 areas, PD and ED score the highest values (59 and 140 respectively). Edge complexity, as quantified by LSI, is very high; while MPS and LPI are relatively low. ENN presents an average of 400 m. Proximity between patches is relatively high (mean PROX = 30.3) but connectivity is very low (mean CONNECT = 8.9).

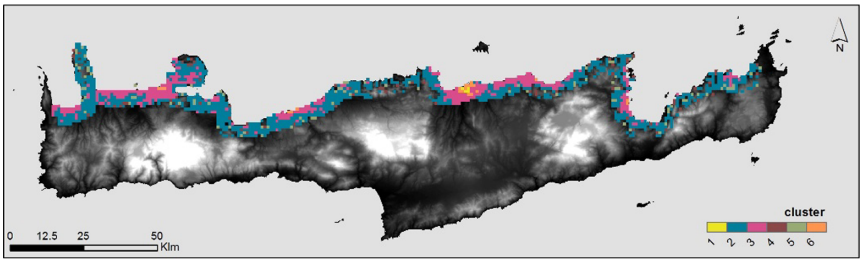

Fig. 8. Spatial distribution of clusters describing built-up typologies in the northern coast of Crete, Source: Own elaboration.

Cluster 1 and Cluster 6 are similar and include tiles with densely built-up urban and periurban areas. Cluster 2 includes 62% of total tiles, displaying transitional areas with relatively low built-up coverage and patch/edge density, but with high degree of dispersion (high ENN) and low connectivity (low CONNECT). These are in most cases agricultural and natural areas, presenting low-density scattered development; or transitional agricultural settlements, located in the hinterland zone and being marginally affected by tourism development and/or periurban processes. Clusters 4 and 5 include areas that are largely non-built and, yet, intact from urban sprawl processes.

5 Discussion and Conclusions

Conflicts between anthropogenic activity and the environment are exacerbating in Mediterranean coastal zones, implying an urgent need to control urban sprawl in such fragile environments. Monitoring coastal urban sprawl could provide the ground for awareness raising and better informing decision-making processes towards the sustainable development of Mediterranean Region as a whole. However, up to now, concrete methodologies for analyzing and monitoring urban sprawl have not been widely applied. In this study, such a methodology is proposed, processing high-resolution spatial data with GIS technology and using spatial metrics for analyzing coastal urban sprawl at a disaggregated level. In this respect, it steps forward previous aggregated level approaches [12, 22, 29].

In Greece, steps undertaken so far to regulate and sustainably manage coastal and maritime space are fragmented and are not integrated into a comprehensive policy framework [30]. This holds true for Crete Island as well, i.e. a remarkable example of Mediterranean insular territory, depicting unique natural and cultural attributes that are heavily

affected by mass tourism and urbanization processes. The study of urban sprawl in the northern coastal zone of Crete shows that different typologies of built-up areas can be identified, locating zones mostly affected by urban sprawl. Results show that coastal urban sprawl is currently heavily affecting respective areas in Crete, with built-up areas expanding in a patchy and scattered way. Quantitative analysis, based on spatial metrics, reveals that 25% of land in the 5 km-width zone along the northern coast is classified as *intense urban sprawl area.* Another 62% of land is classified as transitional areas, with relatively low level of development but high degree of dispersion and low connectivity.

Temporal analysis of urban expansion in the period 1975–2014 shows that pressures on agricultural and natural land will continue; and will expand towards the hinterland zone in the immediate future. This can be attributed to pressures exerted by the mass tourism model. Furthermore, it is clear that tourism carrying capacity in specific zones along the northern coast has already been exceeded, causing severe degradation of Natura 2000 areas, wetlands, etc. [31]. Crete Region, lacking a more concrete spatial planning framework, is marked by a rather uncoordinated urban growth model. Recently the need for an alternative, sustainable tourism model has been underlined, rating high priorities relevant to the protection and preservation of the remarkable Cretan natural and cultural capital. Such values have sparked the Cretan Revised Regional Plan of 2017, in an effort to minimize intense land-consuming activities in coastal and environmentally-sensitive areas. Toward this end, this Plan sets as main spatial targets the change of the so far unsustainable growth model by restraining the expansion of built-up areas in agricultural and natural/forest land and shifting to a more environmentally-friendly tourism model, positively affecting quality of built environment in the largely saturated northern coast. Building restrictions in areas outside the regulated urban planning zones are thus encouraged, seeking to upgrade environmental quality and control spatial deployment of mass tourism; while a redirection towards alternative tourism forms in semi-mountainous inland areas is also pursued.

As possible future research, the proposed methodology could be applied to other coastal areas' examples for enchasing urban sprawl monitoring and reversing its negative effects in Mediterranean coastal zones.

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