Analysis of landscape evolution in a vulnerable coastal area under natural and human pressure

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ABSTRACT
To preserve integrity and functioning of coastal ecosystems services, monitoring and protection actions have to be realized on an ecosystem perspective and consider an integrated observing approach. We implemented a multidisciplinary study, based on remote sensing and geophysical techniques, landscape ecology tools, and geospatial data analysis for monitoring a coastal area (Basilicata Ionian coast) with a high concentration of forest ecosystems services: five Natura 2000 protected sites, intensive agriculture, and touristic infrastructures. The analysis of landscape evolution performed within five protected sites over about 30 years (1985–2013) shows the presence of different processes acting along the investigated coast. Where coniferous forests were involved in marked fragmentation processes geophysical measurements highlighted saltwater infiltrations in superficial layers. Since severe shoreline changes interested the investigated littoral, erosional processes could have increased the saltwater intrusion phenomena favoring the forest degradation and limiting its recovery after fires. Touristic activities do not seem to alter the forest evolution except for very localized segments. The implemented study suggests that the integration of remote sensing and in situ information coupled with landscape ecology perception can be a suitable support tool for planning and management activities in coastal areas (e.g. ecological interventions, and earthen block or barrage construction).

ARTICLE HISTORY
Received 30 June 2018
Accepted 31 July 2018

KEYWORDS
Coast; forest; Natura2000 network; Landsat series; ERT; landscape ecology

1. Introduction
Coastal ecosystems take shape where land and water join to generate environments with a peculiar structure, biodiversity, and energy flows. However, they are particularly sensitive to changes and most of these areas are now struggling to maintain their...
biodiversity and the capacity to deliver ecosystem services and functions (Tian et al. 2017; Camilleri et al. 2017). Changes in coastlands occur due to both human causes and natural phenomena. Among the former, fast and unplanned urbanization caused by increasing tourism and related infrastructures, intensive agriculture, water abstraction, and land reclamation are the most common (Guo and Jiao 2007; Guneroglu et al. 2015; Cai et al. 2016; Xu et al. 2016; Jeuken et al. 2017). Besides the direct impacts produced by anthropogenic factors on coastal areas, it should be considered also indirect effects such as externalization of urban pollutants coming from soil sealing (Prokop et al. 2011) and the discharge of inadequately treated effluents and pharmaceuticals linked to human presence (Pascual-Aguilar et al. 2015). Among natural drivers, unfavorable climatic conditions, complex drainage patterns, predisposing geotopographic features, and seawater intrusion phenomenon are the most widespread agents of disturbance (Barbarella et al. 2015; Gkiougkis et al. 2015; De Filippis et al. 2016). Lastly, levels of coastal stress are exacerbated by global climate change (IPCC 2014) that is expected to accelerate coastal erosion by increasing magnitude and frequency of extreme weather events (Jeanson et al. 2014).

The coupled effect of climate change, disadvantageous natural conditions, and human activities plays a key role in determining rate and size of landscape transformations (Liu et al. 2014) resulting mainly in landscape loss and fragmentation (Tomaselli et al. 2012; Jiang et al. 2014) and reduced functioning of coastal ecosystems services (Alexandridis et al. 2009; Song et al. 2012) such as habitat supporting, pollution mitigation, climate regulation, control of diseases and pests, etc. (Grimm et al. 2008; Sulman et al. 2013; Elmhagen et al. 2015; Greco et al. 2017; Greco et al. 2018). Given the high value of coastal services in driving local economies, adverse impacts on landscape-dependent activities (LePage 2011), such as tourism and fisheries, are likely implying, in turn, unemployment, social instability, and the increase of the socioecological vulnerability of these areas (Metcalf et al. 2015; Bourne et al. 2016).

These dynamics are particularly noteworthy in Mediterranean regions where favorable geopedological and climatic conditions have determined a long-history of human occupation (Leontidou 1993; Airoldi and Beck 2007) that has recently taken the shape of urban sprawl and land consumption as contributing factors to the degradation of these ecosystems (Curr et al. 2000; Calamita et al. 2017; Imbrenda et al. 2013). This picture is further worsened for Italy where national gaps in policy design and implementation, together with an uncoordinated and fragmented management of coastal areas, have paved the way for increased littoralization and consequent high level of soil sealing (Zoppi and Lai 2013; Buono et al. 2015; Falco 2017).

The coasts of Basilicata region, although do not have soil sealing trends comparable to those observed in other Italian coastlands (Marchetti et al. 2017), are already ascertained as vulnerable to degradation for their soil and vegetation characteristics as well as for the management of neighbouring cultivated areas (Imbrenda et al. 2014; Lanfredi et al. 2015). In particular, the Ionian coast includes critical littoral areas in continuous expansion (Amato et al. 2015) where the highest regional values of soil consumption were observed (Marchetti et al. 2017). These areas are of high ecological values (~80% of the coast is included in
the Natura 2000 protected sites) and show complex features as a result of the interplay of social, economic, pedo-ecological, and geomorphological components (Aiello et al. 2013; Greco and Martino 2014).

This complexity needs the adoption of a multidisciplinary approach targeted to capture the interconnections between the different drivers of change and the consequent responses of the socio-ecological system. In particular, in the field of environmental analyses, the use of remote sensing technologies and methods has brought significant advantages in tracking land use/land cover changes (LULCC) to provide a routine monitoring of coastal ecosystems conditions (Nagendra et al. 2013; Cellone et al. 2016; Camilleri et al. 2017). The analysis and interpretation of remote sensing products are successfully used to evaluate habitat conditions and conservation effects (Carone et al. 2009; Liu et al. 2017), especially when coupled with landscape ecology tools (Simoniello et al. 2015; Tian et al. 2017; Zhang et al. 2017) able to directly quantify changes in land cover attributes and to uncover subtle processes involving vegetation status and distribution (e.g. fragmentation, isolation). Finally, connecting geophysical results to vegetation status and landscape complexity, as indicated by satellite imagery and landscape ecology metrics, can help to shed light on the delicate links among vegetation, soil, and coastal erosion (D’Emilio et al. 2012; Dafflon et al. 2017; D’Emilio et al. 2018).

This work evaluates the usefulness of combining multitemporal remote sensing data and techniques, landscape ecology metrics, geophysical field surveys, and geospatial data analysis to study coastal vegetation patterns and to analyze in depth the relationships existing among vegetation patchiness, seawater intrusion, and coastline changes. In particular, complex habitats of five protected areas along the touristic Ionian coast of Basilicata were investigated over a period of about 30 years (1985–2013).

Incorporating diachronic LULCC and the corresponding landscape patterns into environmental analyses can represent a cost-effective support tool for decision-makers to appropriately manage coastal ecosystems, formulate proper land use planning and, ultimately, curb human impacts on the environment (Botequilha Leitão and Ahern 2002; Parcerisas et al. 2012; Li and Yang 2015).

2. Study area

The study is focused on the littoral landscape of the Ionian coast of Basilicata (Southern Italy) (Figure 1(a)). Along this stretch of coast, the dominant landscape element is represented by coniferous forests of Mediterranean pines (mainly, *Pinus halepensis*, and *Pinus pinea*). They prevailently include artificial formations, planted behind the dune system as windbreak barriers to preserve agricultural areas (mainly plant fruit trees and vegetables) in the framework of a large project, started in the Thirties and mostly implemented between Fifties and Seventies by the Land Reclamation Consortium (Margiotta et al. 2015). In addition to its primary ecosystem service, these forests are now functional also for touristic activities and infrastructures. Most of them are included in protected areas, such as national and regional natural reserves and Special Areas of Conservation. Between the mouths of Bradano...
and Basento rivers, the Natural Reserve of Metaponto (about 240 ha) is among the first protected sites created in Basilicata (1972). It was established just to preserve the results of the significant afforestation initiative (protection of agricultural areas) and to safeguard wetland ecosystems at mouths. On the opposed side, the Oriented Natural Reserve of Bosco Pantano di Policoro (located near the Sinni mouth and having an extent of about 500 ha) was established in 1999 and hosts ecosystems of an ancient planitial wood (broad-leaved forest).

Successively in 2005, protection policies were extended to all the areas located in correspondence of the mouth of the five main rivers of Basilicata (Bradano, Basento, Cavone, Agri, and Sinni; Figure 1(b)) including mostly of the previous existing reserves. These sites were inserted in the wider Natura 2000 network of the Basilicata Region and have recently become Special Areas of Conservation (SAC) (Ministerial Decree of 21 February 2013). Within these sites, vegetation is generally composed of coniferous species (e.g. *Pinus halepensis*, *Pinus pinea*); secondary species include *Acacia cianophylla* and eucalyptus (e.g. *Eucalyptus globulus*, *E. camaldulensis*) and other psammophilus species (plants that flourish in moving-sand environments). The ecological asset of the protected site located at the Sinni mouth is rather different, being characterized by the remnant of an important planitial wood (Bosco Pantano di Policoro) containing an exceptional variety of hygrophilous vegetation (e.g. *Quercus robur*, *Ulmus laevis*, and *Fraxinus excelsior*) (Basilicata Region 2010a). It is the only site which is also a Special Protection Area (SPA). Overall, these five Natura 2000 sites have a notable ecological value because containing a unique assemblage of flora and fauna, nested in priority habitats (e.g. Coastal Lagoons, Coastal dunes with *Juniperus spp.*, Mediterranean temporary ponds).

Figure 1. Study area location (a) and boundaries of the investigated Special Areas of Conservation - SAC (b); Geological map of the study area and profiles of geological sections (c) constructed almost parallel to the coastline at an average distance of about 14 km (sect 2-2') and 3 km (sect 3-3') (modified after Spilotro (2004)).
From a geological point of view, the Ionian coastal plain strikes SW-NE for about 70 Km on the water front of the physiographic unit named Fossa Bradanica, delimited to NE from the limestone hills of the Murge and to SW from the Apennines. The coastal plain is characterized by alluvial sediments of the five main rivers discharging into the Ionian Sea; here sandy flat beaches dominate, whereas pebbled areas are sparse (Figure 1(c)). As a consequence of faulting and fissuring, and following sea level changes, the underlying hydrogeological system has been subjected to several seawater intrusion events in past geological eras (Fidelibus et al. 2004). In addition, the construction of 17 dams and small barrages for water storage, the diversion of the main rivers, the massive land reclamation works and the agricultural activities of the neighbouring areas have deeply modified the hydrology of the area, resulting in reduced superficial flow, changes of periods and zones of recharge, increased presence of halophytic species (De Capua et al. 2005; Margiotta et al. 2015) and, ultimately, in salinization phenomena (Polemio et al. 2002; Ricciardi et al. 2008). This is currently further modified by the building of recreational and tourist complexes that have considerably favored tourism flows in the last 20 years (Trivisani et al. 2017), but, at the same time, have altered the distribution and status of flora and fauna also affecting the physico-chemical composition of water (Giacanelli et al. 2015; Di Polito et al. 2016, Ciancia et al., 2018).

3. Data collection

3.1. Satellite data

Multispectral data at 30 m spatial resolution were acquired from the Thematic Mapper (TM) on board the Landsat 5 and from the Operational Land Imager (OLI) on board the Landsat 8. In particular, we processed and analyzed three Landsat 5 TM images acquired respectively on 10 August 1985, 27 June 1998, and 19 July 2006 and a Landsat 8 OLI image acquired on 7 August 2013, all completely covering the study area.

All the selected scenes, downloaded from http://earthexplorer.usgs.gov/, meet the quality standards of the same radiometric and geometric correction and are characterized by absent cloudiness over the study area. They were obtained from path/row number 188/032 and were projected to UTM 33 zone at reference datum WGS 84.

3.2. In situ geophysical data

To delimit the seawater front, five Electrical Resistivity Tomographies (ERTs) were carried out along the whole extension of Ionian coniferous forest during the summer 2010 (Satriani et al. 2011) (Figure 2). ERTs were performed by using a multi-electrode resistivity meter (Syscal R2 Switch48, manufactured by IRIS instruments) able to connect 96 electrodes with a multi-core cable. The hybrid Wenner-Schlumberger configuration was selected for the surveys; such an array configuration is less sensitive to noise and enables a deeper penetration (Dahlin and Zhou 2004; Loke et al. 2010). The Syscal Junior resistivity meter, powered by a 12-V battery, is capable of injecting up to 1.500 mA of current into the ground. Measurements were carried out over a
period of 500 ms, during which the polarity of the current electrodes was reversed in order to minimize electrode polarization effects. We used solid stainless steel electrodes of about 20 cm long and 2.0 cm in diameter; the electrodes were inserted in holes drilled into the soil and, then, watered with a dilute saltwater solution to minimize electrical contact resistance between the electrode and the dry soil.

Resistivity profiling was carried out on quite flat areas along a direction perpendicular to the coastline with a 10 m inter-electrode separation and profile length of 470 m, which resulted in a depth of investigation of about 70 m.

3.3. Ancillary data

To refine land cover classifications, evaluate shoreline changes, and better interpret land trajectories, we used different ancillary data and OCG (Open Geospatial Consortium) services from various sources:

- Corine Land Cover (CLC) maps for the years 1990, 2000, 2006 and 2012;
- High-resolution Google Earth images;
- Aerial orthophotos (1:10,000, with a resolution less than 1 m) for the years 1988, 1997, 2006, and 2013 (Regional SDI - Spatial Data Infrastructure of Basilicata, https://rsdi.regione.basilicata.it/; National SDI, https://pcn.minambiente.it/);
- Protected areas boundaries (Regional SDI of Basilicata, https://rsdi.regione.basilicata.it/)
4. Methods

4.1. Processing of Landsat data for diachronic land cover mapping

Landsat images were firstly preprocessed by applying the transformation of digital numbers into radiance units and, then, into reflectance using the NASA-GSCF calibration coefficients (Chander and Markham 2003; Barsi et al. 2007) (see also https://landsat.usgs.gov/using-usgs-landsat-8-product). The selected images appear with clear atmosphere over the study area and show a high data quality. For the purpose of this study (multitemporal comparison of landscapes), the land cover maps were obtained directly from calibrated reflectance bands since no atmospheric correction is specifically required (Song et al. 2001; Lin et al. 2015).

For the land cover classification, we adopted the Iterative Self Organizing Data Analysis (ISODATA), one of the most utilized and robust methods in the multispectral and multitemporal unsupervised classification (Tou and Gonzalez 1974; Simoniello et al. 2008; Pope and Rees 2014; Varamesh et al. 2017). As input for the unsupervised algorithm, for both OLI and TM we used all the VNIR and SWIR bands (30 m) excluding the thermal bands for the low spatial resolution (100 m and 120 m, respectively). For L8-OLI data, also bands 1 and 10 were not included. Band 1 is significantly correlated with blue band 2 and designed for monitoring waters and aerosols, whereas band 10 is designed for cirrus identification; therefore, they contain limited additional land surface information.

The labelling process of the resulting clusters was implemented by visual interpretation and ancillary data integration (CLC maps, Natura 2000 field surveys, orthophotos, and Google Earth images). Classification accuracy was evaluated through a stratified (size proportionate) random sampling (Olofsson et al. 2014).

The image processing and classification were carried out using ENVI image analysis software; whereas the labelling process and spatial analysis were implemented in GIS environment (QGIS 2.18.3, GRASS 7.0.5).

4.2. Landscape metrics for analyzing vegetation patterns

To assess the landscape evolution and analyze the ecological dynamics of vegetation patterns, we adopted concept and metrics of Landscape Ecology. Landscape metrics
are considered an appropriate mean to investigate both macroscopic and elusive ecological phenomena reflecting the impacts of both anthropogenic and natural factors (Huang et al. 2017; Vaz et al. 2017).

In particular, we performed a hierarchical analysis at landscape, class, and patch level on the historical set of land cover maps (1985–2013) obtained from satellite data elaborations. The selection of metrics was focused mainly on their ability to provide information on vegetation fragmentation, connectivity, shape complexity, and diversity as key features to understand the role of anthropic and natural stressors on the ecological equilibrium of the coastal area. On the basis of our previous experience in the region (Simoniello et al. 2006; Carone et al. 2010; Imbrenda et al. 2014) at landscape and class level we evaluated: the landscape diversity (SHDI) and evenness (SHEI), the number (NP) and the mean dimension (MPS) of the patches, the distance between closer patches of the same class (ENN), the level of interspersion among a patch of a given class and adjacent patches of other classes (IJI), the compactness (internal connectivity) of a patch (GYRATE), and the level of patch shape complexity/naturality (FRACT) (McGarigal et al. 2012).

At patch level, the FRACT and GYRATE indices were combined to obtain a categorized map of Patch Structure Vulnerability (PSV).

\[
PSV = \left[ \text{GYRATE}_{t_2} - \text{GYRATE}_{t_1} \right] \cap \left[ \text{FRACT}_{t_2} - \text{FRACT}_{t_1} \right]
\]

where \( h_{ijr} \) = distance (m) between cell ijr (located within patch number j and class i) and the centroid of patch ij, based on cell center-to-cell center distance; \( z \) = number of cells in the patch ij; \( p_{ij} \) = perimeter of the patch ij; and \( a_{ij} \) = area of the patch ij; \( t_1 \) and \( t_2 \) are respectively the start and the end of the considered time period (1985 and 2013).

Gyrate represents the mean distance between each cell in the patch and the patch centroid. Gyrate is 0 in the case of a patch consisting of a single cell and rises without limit as the patch increases in extent (McGarigal and Marks 1995). It is conceived as an estimator of patch connectivity (extensiveness and compactness) considering that the larger the mean distance, the smaller the probability of patch core exposition to disturbance.

Fract values range from 1 for shapes with simple perimeters (e.g. circles or squares) and approaches 2 for shapes with highly convoluted perimeters. It is a suitable measure of the regularity of the patch structure considering that, generally, simpler structures are associated to less natural vegetation patches; therefore, low Fract values highlight possible anthropic influences.
The PSV map was categorized to gain knowledge about the vulnerability of vegetation configuration, evaluating the coupling of the sign of index difference and considering that:

\[ \Delta \text{Fract} > 0 \] indicates increasing levels of naturalness consisting in more irregular patches;

\[ \Delta \text{Fract} < 0 \] indicates decreasing levels of naturalness consisting in more regular patches possibly connected with the effects of surrounding human activities;

\[ \Delta \text{Gyrate} > 0 \] indicates larger mean distances between edges and the patch core suggesting a lower vulnerability to external disturbance;

\[ \Delta \text{Gyrate} < 0 \] indicates shorter mean distances between edges and the patch core suggesting a greater vulnerability to external disturbance.

The selected metrics were computed using the public domain software FRAGSTAT 4.1 (McGarigal et al. 2012), then, integrated and analyzed in GIS environment (QGIS 2.18.3, GRASS 7.0.5).

4.3. In situ surveys for assessing seawater intrusion

The ERT is an active geophysical method largely applied to obtain high-resolution images of the subsurface resistivity pattern, i.e. information about the spatial distribution of the electrical resistivity (or equivalently the electrical conductivity) in the subsoil and/or the inner of the investigated structure.

To explore the large resistivity contrast between saturated and unsaturated zones, the resistivity data collected along the coast were inverted to create a pseudo-section of resistivity along each of the five survey lines; thus, a model of earth subsurface and geoelectric sections were produced. The in situ measurements (raw data) provide the so-called apparent electrical resistivity, which does not represent the actual true spatial distribution of the electrical resistivity in the ground. Therefore, to obtain the actual subsurface configuration, we applied the robust and widely adopted RES2DINV software (Geotomo Software 2002; Satriani et al. 2012) for the inversion of the acquired 2-D apparent resistivity. The algorithm of RES2DINV is based on a least-squares optimization technique (Loke and Barker 1996) for the global minimization of the cost function representing the distance in data space between the collected data and model data. Model data are computed according to the exact forward model in a 2-D geometry, where the investigation domain is discretized by rectangular blocks of increasing extent with the depth. Before the minimization stage, raw data were pre-processed by applying a despiking procedure to remove the extreme readings from the dataset.

Since the electrical resistivity of a rock/soil is controlled by different factors (water content, porosity, clay content, etc.) (see, e.g., Calamita et al. 2017), for any particular rock/soil type, there is a wide and nonexclusive range of resistivity that cannot be directly read in terms of lithology. Therefore, to check and interpret the derived resistivity pseudo-sections from a lithological point of view, we constructed different geological sections orthogonal to the resistivity profiles (almost parallel to the coastline). Then, on the basis of such information, profiles showing the seawater mixing zone were elaborated.
5. Results and discussion

5.1. Land cover maps (1985–2013)

The land cover maps obtained from the processing of the four Landsat data acquisitions (1985, 1998, 2006, and 2013) are shown in Figure 3. Each of them identifies six classes: coniferous forests, broad-leaved forests (mostly hygrophilous species), transitional woodlands and shrublands (bushes and vegetation in evolution), sparse vegetation (mainly dune and pioneer vegetation, e.g. psammophilus sp.), non-vegetated areas (including urban areas, bare soil, beaches, and dunes), and anthropic vegetated covers (principally cultivated and bordering vegetation). The overall classification accuracy for land cover maps is about 85%.

As clearly visible in the maps, the Ionian landscape is largely dominated by coniferous forests, they are mainly intermixed with transitional (woodlands and shrublands) and sparse vegetation; the presence of large broad-leaved forests is almost fully localized southwestern. Non vegetated areas along the inland border principally represent bare soil of cultivated area, without plantations on the image acquisition dates, whereas the stretches along the coastline locate beaches and pre-dunes.

The obtained land covers represent the input eco-mosaics for the evaluation of landscape ecology metrics.

5.2. Vegetation patterns as revealed by landscape metrics

5.2.1. Landscape scale

The landscapes within the protected areas show quite similar values of landscape diversity in 1985 for the five sites (Figure 4) evidencing the presence of a dominant cover (SHDI~1.5, Shannon Diversity Index). In 1998, the Bradano and Sinni SAC display the highest variations compared to the previous values, with an increase in landscape diversity for the first site and a reduction for the second one. In 2006, there is a realignment tendency to the old conditions except for the Cavone site where the landscape heterogeneity continues with a slight reduction. Finally, in 2013, the Cavone site shows the lowest diversity value highlighting an unbalanced land cover distribution. On the contrary, in the Sinni SAC the diversity level further increases.

All the sites, during the considered periods, show quite low mean values of patch shape complexity (Fract variability 1.14–1.23) indicating a general strong influence of the human component.

In 1985, the landscape of the first three protected sites from NE-SW direction is principally covered by the coniferous forests (Bradano 36.8%, Basento 32.5%, and Cavone 33%). The Agri site is largely characterized by sparse and transitional vegetation (63%) with a discrete presence of conifers (~20%) and non vegetated covers (Figure 5). The Sinni area is, instead, characterized by broad-leaved forests (~40%); coniferous stands cover less than 1% of the area.

In the following periods, Bradano, Basento, and Cavone sites are still dominated by coniferous forests, but their similarity in land cover distribution slightly changed over time; they seem to be involved in different vegetation evolution processes.
The Bradano SAC (Figure 5(a)) shows a quite low variability of conifers surface up to 2006, then it is involved in an enlargement phase resulting in a net surface increase of more than 45 ha in 2013 (Figure 5(f)). The conifers within the Basento SAC (Figure 5(b)) are interested by alternate processes (expansion 1985–1998, strong...
contraction 1998–2006, and recovery 2006–2013) returning the total surface back to the 1985 conditions (Figure 4(f)). The site is also characterized by a continuous expansion of non vegetated areas. The last of these three sites, the Cavone SAC (Figure 5(c)), points up a progressive enlargement of coniferous stands covering more than 55% of the protected surface in 2013.

The evolution of the Agri SAC (Figure 5(d)), similarly to the Basento one, is characterized by a continuous increase of non-vegetated surfaces (total added surface ~150 ha), but differently to that littoral, it also shows a continuous enlargement of coniferous forests with a net increase of about 35 ha. For the Sinni SAC/SPA (Figure 5(e)), the broad-leaved forests after a first growth period (1985–1998), show a phase of surface contraction returning back to an extension similar to that of 1985 (~5 ha more in 2013). The relative presence of coniferous species was quite stable during the first 20 years and increased only in the last period (2006–2013).

Such changes of forested area in the five protected areas were principally linked to a reduction of sparse and transitional vegetation in favour of coniferous stands and non vegetated area (Figure 5(f)).

To better analyze the ecological dynamics of vegetation patterns, understand the different evolution processes of such difference in landscape changes among the protected sites, we analyzed results from class and patch level metrics (Sections 5.2.2 and 5.2.3).

5.2.2. Class scale
Metrics at class level allow a deep interpretation of the general processes highlighted at landscape level. Figure 6 displays the evolution of ecology metrics for the protected area of Bradano (data are normalized to the temporal mean to be shown in a single graph per cover). Here, coniferous plantings show a first period of contraction with loss of small patches followed by a fragmentation phase up to 2006. Indeed, the coniferous surface remains quite stable in this period (Pland) with a strong reduction of the patch number associated to an increase of their mean size in 1998; conversely, in 2006 patches become more numerous and on average smaller and vulnerable (NP

Figure 4. Shannon diversity index: measure of landscape diversity weighted to the relative cover abundance.
increase, MPS and Gyrate decrease). By taking into account the very slight surface increase, metrics also describe a combined stating phase of a recolonization process with the generation of new small patches (Cocca and Cocca 2005). Actually, in 2013, coniferous stands enlarge (Pland increase) with a tendency to compaction: small patches are merged with bigger ones (NP reduction, MPS increase) rising the distance respect to other coniferous patches (ENN increase) and the resistance of their core to external disturbances (Gyrate increase). Physical connectedness (Cohesion) and structure regularity (Fract) do not show appreciable variations.

Broad-leaved forests (mainly hygrophilous species) show processes of consolidation and expansion/colonization up 2006. In particular, during the first time interval (1985–1998, consolidation phase) the surface increase is coupled with the presence of fewer patches that are larger (MPS increase) and more interspersed (IJI increase). During the second time step (1998–2006, colonization phase), the further rise in surface is, on the contrary, characterized by an increase in patch number and a reduction in mean patch size and interspersion level. In 2013, broad-leaved surface strongly shrinks and the remaining patches exhibit a drastic size reduction and core resistance decline. This, coupled with an interspersion increase and a reduced compactness (Cohesion decrease), suggests that abrupt changes have affected such a cover (e.g. fires occurred mainly in recent years) (Basilicata Region 2010b).

Figure 5. Changes in land cover distributions during the analyzed three decades for the five investigated Special Areas of Conservation (a–e). Variations of land cover surfaces expressed in hectares (ha) between 1985 and 2013 (f).
Transitional wood/shrublands surfaces strongly decline during the first 20 years and slight recover only in the last period (2006–2013). Such a decline is mainly characterized by a fragmentation process coupled with a strong patch erosion (NP increase with fall of MPS, Gyrate and Cohesion). In the recovery process of last period, the patches become fewer and larger (NP decrease, MPS increase) with higher levels of compactness (Cohesion rise) and core resistance to external vulnerability (Gyrate rise). The shuttering of this class appears to be connected with recolonization processes favouring the enlargement of the forested stands of broad-leaved and coniferous species.

Figure 6. Evolution of ecology metrics evaluated at class level for the Bradano Special Area of Conservation. Percentage of landscape surface (PLAND); number of patches (NP); mean patch dimension (MPS); distance between closer patches of the same class (ENN); level of interspersion among a patch of a given class and adjacent patches of other classes (IJI); compactness (internal connectivity) of a patch (GYRATE); and the level of patch shape complexity/naturality (FRAC). The values of the metrics are normalized to the respective temporal mean.
Extent of sparse vegetation increases in the period 1985–2006 and decreases between 2006 and 2013. Despite this alternation, NP incessantly rises and Gyrate continuously decreases. The joint reading of these indices with the variability of the other metrics, particularly mean patch size and distance (ENN), reveals an expansion with extension of patch strips up to 1998 and the creation of new small patches up to 2006. Then, a fragmentation process affected the cover (strong MPS decrease). This behaviour is possibly linked with recurring fire phenomena that in some periods have enlarged the presence of herbaceous species at the expense of more structured vegetation. The natural recovery of vegetation has ultimately generated, on the one hand, a reduction of this cover and, on the other, a patchy configuration of this class resulting in a large number of small nuclei.

Anthropic vegetated covers include agricultural areas that have notably increased in recent times as a result of the specialization of the Metapontum Plan in the intensive production of vegetables and plant fruit trees (Margiotta et al. 2015). However, it is worthy of note that these additional surfaces devoted to agriculture have a fragmented configuration (particularly after 1998) typical of the Mediterranean landscapes, often intermixed with other types of covers. This is indicated by the final higher number of patches having a reduced extension (MPS decrease) and by the increased interspersion value (IJI) accompanied by a shorter distance between similar patches (ENN decrease).

Non vegetated covers (i.e. dunes, bare soils, beaches, and urban areas) show slight variations in surface dimensions with a patch enlargement and fusion (NP decrease, high MPS and Gyrate increase) in the first period, erosion up to 2006 (NP decrease), and a slender recovery with high interspersion among other covers during the last period.

Being this class a mix of different cover typologies (natural and anthropic) with similar spectral behaviour, it is not easy to infer information from land cover maps and landscape indices alone, therefore, we jointly evaluated the available orthophotos. The main variations of this class in the Bradano SAC seem mainly linked to the complex balance between accretion and erosion processes affecting the protected area and including especially beach and dune areas.

Within the Basento SAC, coniferous expansion of the first period is characterized by inclusion phenomena of small patches into larger ones (NP decrease and MPS, ENN, and IJI increase); then, coniferous stands were affected by a strong fragmentation process up to 2006 (high NP rise and strong MPS and Gyrate reduction), which reversed in the recent period (Figure 7(a)). The recovery of coniferous forest brings the cover surface to the conditions of 1985, but with patches more vulnerable (smaller Gyrate and Fract).

For the Cavone SAC, the continuous conifer surface expansion during the whole investigated period (Figure 7(b)) is driven by a consolidation process with inclusion of smaller patches up to 2006 (NP decrease and MPS, ENN, and IJI increase), and, then, also by creation of new small patches (Pland increase with NP rise and MPS reduction).

Also in the Agri SAC coniferous forests increased their surface but with different processes and timing compared to the Cavone site. In the first time interval, the
slight increase in the cover extent (Pland) is coupled with a mean patch size reduction and a very high increase in patch number with respect to the total extent advance (Figure 7(c)). Therefore, the metrics seem to describe the presence of two main contrasting processes affecting the cover between 1985 and 1998: a conifer portion involved in forest expansion and a portion affected by fragmentation processes. In the following periods, the cover expanded by enlargement of the patches with inclusion of the smaller ones (1998–2006: high NP reduction, MPS, IJI and Gyrate rise) and by elongation of the patches with the creation of lengthy strips (2006–2013: metric variations similar to those of the previous period with the exception of Gyrate which decreases).

The presence of coniferous forests within the Sinni SAC is very trifling particularly up to 2006 (extension less than 1 ha), during the last period increases (even if still small in size compared to the other vegetated covers) with creation of new parches (NP, MPS and Gyrate increase;) within a matrix of the same cover (IJI and ENN reduction) (Figure 7(d)). The largest and precious (from a conservation point of
broad-leaved forest cover of the Sinni area (Figure 7(e)) shows a surface rise in 1998 characterized by a patch enlargement and fusion (NP reduction, high MPS increase, IJI and Gyrate rise). Subsequently in 2006, the slight broad-leaved surface decrease is mainly due to erosion and fragmentation processes that continue also in the following period. In 2013, the surface extension is similar to that of 1985, but with different arrangement: the cover is generally more fragmented (higher NP, lower MPS) even if the resistance of patch core to external disturbances is on average increased (higher Gyrate) compared to the first year.

Similarly to the Bradano site, modifications of forested stands mainly involved transitional and sparse vegetation also in the other protected sites. They fragmented when forests expanded and extended when forested covers reduced (see details in Supplementary Materials).

5.2.3. Patch scale
Results from metrics evaluated at patch level are shown in Figure 8. The increase in patch border regularity (negative ΔFract) mainly involves the Cavone and Agri areas...
By considering also results at higher hierarchical levels (previous sections), for the first site regularity is mainly linked to the expansion of coniferous forest up to the limit of roads and to agricultural activities bordering the west side of the forests. For the Agri SAC, the lower level of naturality can be principally linked to the contraction of the touristic harbor and related infrastructures that changed the configuration of neighboring vegetation. These areas also show a reduced resistance of patch core to external disturbances (negative $\Delta$Gyrate).

The PSV map summarizes both such indices highlighting at the same time the level of vulnerability for increased level of human influence and exposures of patch core to external disturbances in the period 1985–2013. Blue areas display patches that became more resistant and more natural (i.e. patch border configuration are less modified by human actions), and therefore characterized by low vulnerability. On the contrary, the areas in magenta (very-high vulnerability) were affected by modifications that threatened the vegetation patch resistance and potentially can provide reduced ecosystem services. A lower level of vulnerability is associated to patches with a higher degree of naturalness, but showing negative values of $\Delta$Gyrate (i.e. less resistance to external disturbance) that suggests the possible development of degradation processes (high vulnerability, orange class). The green class indicates the intermediate vulnerability level (medium) related to an increased human pressure (rise in patch shape regularity) that is associated with an increased patch resistance to disturbance given the larger mean distance between edges and patch core.

To search for proximate causes of these findings, geophysical measurements have used to complement the landscape analysis. In Section 5.4, details on vegetation patterns around the field surveys are shown.

### 5.3. Seawater intrusion phenomena: ERTs analyses

The range of the measured electrical resistivity is about $0.2–300 \ \Omega \cdot m$ with the exception of the tomography acquired between the Basento and Cavone rivers (Profile 3). The ERT images and their interpretation in term of seawater limits are shown in Figures 9 and 10, respectively.

#### 5.3.1. Profile 1

The resistivity survey of profile 1 was carried out at a distance of about 60 m from the coast and almost parallel to the Bradano river mouth. The maximum apparent electrical resistivity measured in this profile is about $300 \ \Omega \cdot m$ (Figure 9(a)). The alluvial (dry) formation extends up to a depth of 8 m inland. The low apparent resistivity values ($0.3–2.0 \ \Omega \cdot m$) indicate that the influence of seawater is up to about 370 m from the coastline (Figure 10(a)).

#### 5.3.2. Profile 2

The ERT of profile 2 (Figure 9(b)) was acquired at a distance of about 10 m from the sea. The interpretation of the resistivity image with the geological cross section indicates, as for the previous profile, apparent resistivity values ($0.3–2.0 \ \Omega \cdot m$) influenced by the presence of seawater. Such an influence is present up to 320 m from the
coastline (Figure 10(b)). Alluvial deposits (300 $\Omega$m) are detectable in the shallow part of the ERT.

5.3.3. Profile3
The profile between Basento and Cavone rivers starts from 2 m from the sea. The inspection of the obtained tomography (Figure 9(c)) shows resistivity values varying in the range 0.2–4000 $\Omega$m. The very low resistivity layer could be due to the influence of sea water in alluvial material, whereas the portion from the middle to the left part of the image can be associated with not saturated alluvial material in which some high resistivity nuclei ($\rho > 1000 \Omega$m) are embedded (Figure 10(c)). The high resistivity material present on the surface towards the sea (about 400 m along the profile) can be associated with dry sand.

5.3.4. Profile4
The ERT section between Cavone and Agri rivers, sampled at about 20 m of distance from the sea (Figure 9(d)), shows three layers at different depths: down to 10 m,
alluvial dry material with higher resistivity values (30 $\Omega m \langle \rho \rangle$ 70 $\Omega m$); from 10 m to about 40 m there is the presence of seawater in alluvial material (0.5 $\Omega m \langle \rho \rangle$ 5 $\Omega m$); then lying on blue clays (8 $\Omega m \langle \rho \rangle$ 20 $\Omega m$). For such a profile, the influence of seawater is along the entire section below 10–30 m (Figure 10(d)).

5.3.5. Profile 5
The last tomography image (Figure 9(e)) was acquired along the SW boundary of the coniferous forest stand at 40 m from the sea. It highlights three homogeneous electrical layers. The shallow deposits (about 10 m) are correlated with dry alluvial sediments lying on saturated alluvial deposits (12 $\Omega m \langle \rho \rangle$ 30 $\Omega m$), then, from 10 m to about 40 m there is the presence of seawater in alluvial material (0.3 $\Omega m \langle \rho \rangle$ 2 $\Omega m$) lying on blue clays (about 4 $\Omega m$). As for the previous profile, the influence of seawater is along the entire section, but with a more uniform intrusion below 10 m (Figure 10(e)).

5.4 Linking ERT to landscape metrics
5.4.1. Profile 1
ERT 1 falls in the SAC of Bradano mouth (Figure 10); it is located in correspondence of an area occupied by transitional wood/shrubland in 1985 (see Figures 10(a) and 11(d)) and regressed to sparse vegetation in 2013 (Figure 10(b) and 11(e)). This land change has occurred due to frequent fires triggered by the widespread presence of death wood in fragile environments subjected to repeated attempts of restoration.
The high plant density among artificially planted coniferous trees results in a higher competitiveness and a higher probability of mortality (Basilicata Region 2010b).

Landscape metrics renders a composite picture of the examined areas where detrimental and beneficial phenomena interwine (Figure 10(c)). The area crossed by ERT proves to be widely affected by a tendency to fragmentation and to hosting less structured vegetation types (herbaceous species) as a consequence of depth and maximum inward position reached by the salt wedge (Figure 10(f)) linked to retreating coastline (see coastlines in Figure 10(d)). The seawater mixing zone is less shallow after around 370m from coastline and the presence of alluvial deposits allows the growth and strengthening of afforested species both inland and towards South East. Conversely, stands less distant to the coastline suffer also of a strong competitiveness with salt tolerant species (mainly *Acacia saligna*) (Cocca and Cocca 2005; Basilicata Region 2010b).

### 5.4.2. Profile 2

ERT 2 falls in the SAC of Basento mouth (Figure 11) within a reforestation site established in Fifties where transitional vegetation alternates with coniferous species. This area has recently undergone a heavy land transformation linked to the building of infrastructures and tourist facilities in a zone prevalently subjected to erosion (Figure 11(d)). This has created an alteration of the complex wetland mosaic by modifying the morphodynamic equilibrium, accentuating the impact of the acting erosion phenomena, and, ultimately, causing harm to floral and faunal communities (Basilicata Region 2010c). Depth and position of saline front derived from ERT 2 (Figure 11(f)) confirm these observations. Most of coniferous plantations appear fragmented and
vulnerable due to touristic infrastructures and the high fire incidence coupled with saltwater infiltration inhibiting the natural regrowing of conifers after fire events.

5.4.3. Profile 3
A typical coniferous planting, located between Basento and Cavone mouths, hosts ERT 3 (Figure 12). The survey highlights a less stressed situation where the presence and thickness of saline intrusion is limited. Current arrangement of coniferous forests (2013) suggests a tendency to compaction in comparison with past configuration (1985). The expansion of forests involves also areas towards the coastline and this should be related to the observed accretion phenomena (Greco and Martino, 2016). However, landscape metrics underline a heterogeneous picture. Old formations (1985) show medium-high level of vulnerability, whereas new stands exhibit fair conditions (medium vulnerability) facilitated by accretion phenomena. Probably, despite the overall increased connectivity between forest patches, lack of thinning practices has produced competitiveness between old coniferous plantings with a subsequent excessive density and partial deterioration of old stands (Basilicata Region 2009a).

5.4.4. Profile 4
ERT 4 falls in the SAC of Cavone mouth within a characteristic coniferous planting (Figure 13). Here the tendency to compaction of vegetation patches is clearly recognizable helped by a lesser intensity of coastal erosion processes (Basilicata Region 2009a). Even though the tomography has been carried out in correspondence of an eroded stretch of coast, it displays a pervasive intrusion of saline front that, however,
is deeply located allowing the presence of forest vegetation. Metrics account for a complex phenomenon. We observe improved conditions of the preexisting (1985) coniferous stands (light green) and an ecologically imbalanced state of the new formations (purple) expanding towards the coastline. This enlargement towards the coast makes new stands more vulnerable due to exposure to salty winds and competition with salt-tolerant plants, so that vegetation assumes not optimal configuration features.

5.4.5. Profile 5
ERT 5 is located between Agri and Sinni mouths (Figure 14) in an area covered by coniferous species which appear recently planted in 1985 (see in Figure 14(d) the geometrical arrangement of rows) so that were classified as transitional woodland/shrubland. However, saline wedge is not too shallow and vegetation follows patterns already observed in Profile 4. In other words, reforested stands have gained areas creating a greater degree of compactness, but what was forest in 1985 (both coniferous and hygrophilous species) remains more ecologically stable (light green). On the contrary, new formations derived from the growth of transitional wood or sparse vegetation show a not optimal arrangement generally linked to local conditions (morphological depressions and disturbance of alien species such as *Acacia saligna*) (Basilicata Region 2009b).

6. Outlines on the protected sites
The main results obtained from the integrated analysis of remote sensing data, landscape metrics, *in situ* geophysical surveys and ancillary data are summarized in Table 1.
Generally, response of vegetation to external factors has a very local nature depending on the intertwining of different aspects connected to coastline dynamics, anthropic pressure, topography and vegetation species present in the analyzed sites. The positive effects of Natura 2000 sites established in 2005 are recognizable in all the sites showing a general improved ecological balance in the last investigated period (2006–2013).

7. Conclusions

The integrated study implemented on the Ionian coast of Basilicata draws a picture of diversified forest status, where direct touristic impact has localized effects and the general conditions of vegetation is largely driven by a combination of factors linked to large forest fires, agricultural activities and seawater intrusion coupled with not adequate agro-forestry maintenance.

The climate change scenario proposed for the Mediterranean area indicates a substantial change in the hydrologic budget by the end of this century (increase in temperature and evaporation, concentration of rainfall in short periods with consequent increase in extreme events as floods or droughts, late frost events, etc.) (Magnan 2009; Jeanson et al. 2014; Greco et al. 2018). Such a forecast has relevant implications for the coastal areas, because a shortage of freshwater in these areas will promote seawater intrusion and soil salinization. At the same time these extreme events can exacerbate the effects of scarce maintenance, favoring the expansion of phytosanitary problems (e.g. increase of pathogen and parasite attach, reduced forest resilience).

Therefore, it is mandatory to implement mitigation and adaptation strategies to be able to preserve ecosystems and their services. The adopted approach combines the remote sensing peculiarities (synoptic view, multi-temporal availability) with those of landscape ecology tools (holistic assessment) and geophysical techniques (local details,
Table 1. Main dynamics involving vegetation pattern in the five protected areas of the Ionian coast.

| Protected site | 1985–1998 | 1998–2006 | 2006–2013 | Notes |
|----------------|-----------|-----------|-----------|-------|
| Bradano        | Loss of coniferous forest: small patches eroded and signs of an initial stage of fragmentation. Fragmentation of transitional vegetation. | Continuous fragmentation of coniferous forest with interspersion of new sparse vegetation nuclei. Fragmentation of transitional vegetation evolved to broad-leaved forests | Recovery of coniferous forest with tendency to compaction. Recovery of transitional vegetation with drastic broad-leaved forests decline. | Influence of seawater intrusion in less deep layers. Strong competition with salt tolerant species (mainly *Acacia Saligna*) in particular after fire events. |
| Basento        | Expansion of coniferous forest by inclusion of small patches with fragmentation of transitional and sparse vegetation. | Fragmentation of coniferous forest with expansion of transitional vegetation, even if with thin and instable strips; continuous fragmentation of sparse vegetation. | Recovery of coniferous forest to 1985 conditions but with more vulnerable patches (smaller Gyrate and Fract); slight regression of transitional vegetation; continuous fragmentation of sparse vegetation | Influence of seawater intrusion in less deep layers. Strong competition with salt tolerant species (mainly *Acacia Saligna*) in particular after fire events. Localized impact of touristic infrastructure |
| Cavone         | Expansion and consolidation of coniferous forest by inclusion of smaller patches | Expansion of coniferous forest by inclusion of smaller patches | Expansion of coniferous forest with new small patches | Unique site with a consistent and constant coniferous expansion. Due to the physical limit of road presence, forest stands show a highly regular configuration. |
| Agri           | Portion of coniferous forest in expansion and other parts in fragmentation, since the increase of patch number is too high compare to the increase in surface; fragmentation of transitional vegetation; patch erosion and attrition of small patches for sparse vegetation | Continuous expansion of coniferous forest by inclusion of smaller patches; erosion of small patches for transitional vegetation and continuous fragmentation of sparse vegetation | Continuous expansion of coniferous forest by inclusion of smaller patches within strips of greater patches (Gyrate reduction); further erosion of small patches for transitional vegetation and continuous fragmentation of sparse vegetation | Coastal modifications for touristic harbor building: some bordering vegetation patches seem suffering whereas coniferous forests continue to expand. Localized impact of touristic infrastructure. |
| Sinni          | Expansion of broad-leaved forests with patch enlargement and fusion. | Erosion and fragmentation processes involved broad-leaved forests with a slight surface reduction. | Further fragmentation of broad-leaved cover reaching an extension similar to that of 1985, but with higher resistance of patch core to external disturbances; Signs of conifers colonization in the broad-leaved matrix with creation of new small patches. | Returning of broad-leaved forest to the extension of 1985 but with different arrangement: the cover is generally more fragmented even if patches are less vulnerable to external disturbances. Reduction of farming pressure. |
non-invasive soundings) to follow different littoral processes and can represent a suitable support tool for planning and management activities in coastal areas, such as the identification of the most appropriated sites for restoration and ecological interventions, for the construction of earthen block and barrage as well as for monitoring the effects of already implemented mitigation activities.

Acknowledgements

Activities partially founded by PRO-Land project - “Assessment methodologies for controlling land degradation processes and impacts on the environment” (Programma Operativo FESR Basilicata 2007-2013).

Disclosure statement

No potential conflict of interest was reported by the authors.

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