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Ecosystem functions at the island scale: a contribution to the design of ecological structure

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ABSTRACT

The concept of ecological structure (ESt), as implemented through spatial planning, has been recently used to protect ecosystem functions (EFs) and services and their contribution to human well-being. This study intends to provide an exploratory analysis to operationalize the inclusion of EFs in the design of ESt in territories lacking detailed individual studies on EFs. The objective is to advance this concept in small island ecosystems and use Pico Island (Portugal) as case study. The proposed methodology identifies EFs contributing to the objectives of ESt. It uses (i) geographic data available from studies on individual EFs and (ii) definition of territorial units (TUs), based on biophysical features, used as cartographic units to assign and map remaining EFs. A total of 15 EFs were selected among three main categories: natural regulation (10), support (3) and cultural (2) functions. Geographic data are available for carbon storage and groundwater recharge. To assign the remaining EFs, a total of 86 TUs were defined. The performed analysis suggested that the use of EFs, along with multi-criteria decision-making techniques, could successfully contribute to define ESt and integrate it into spatial planning on Pico Island and other small islands systems.

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Ecosystem service; spatial planning; environmental management; small Island; Azores

1. Introduction

The concept of conservation has been gradually changing in recent decades; from the protection of species to the protection of whole ecosystems, their concomitant functions and contributions to human well-being through the provision of ecosystem services ([MEA] Millennium Ecosystem Assessment 2005). This approach has been encouraged in application of spatial planning and management, with a conscious integration of the protection and enhancement of natural processes and functions through ecological structure (ESt) (COM 2013). For example, European Union (EU) leaders, recognizing that the loss of biodiversity could not be reversed by the target date of 2010 (COM 2011a), adopted a new target 'to halt the loss of biodiversity and the degradation of ecosystem services by 2020' by defining a long-term target and vision and a new biodiversity strategy: to protect, value and appropriately restore biodiversity and the ecosystem services it provides (its natural capital) by 2050 (COM 2011b). This last approach to nature conservation brings new challenges to spatial planning and land management and requires novel rationales and methodologies. Defining the ESt can aid local decision-making (e.g., in municipalities), as it integrates information and spatial data on ecosystem functions (EFs) that can provide insight into management of local resources. Small island systems are especially amendable to this approach since they must consider ecological and economic goals in relatively small, complex landscapes.

Small-sized and well-defined territorial boundaries of small islands and their particular vulnerability to natural hazards and land-use disturbances (Mimura et al. 2007; Rietbergen et al. 2007) pose additional challenges in the search for alternative economic activities and allocation of development sites. Spatial planning is extremely complex when land area for development or conservation is limited. For this reason, integration of natural processes and functions into spatial planning and land management instruments should favor the provision of crucial ecosystem services.

Methodologies to assess and design ESt and integrate ecosystem services in spatial planning are emerging. Liquete et al. (2015) proposed a methodology to identify and map elements of green infrastructure at a landscape level based on the concepts of ecological connectivity, multi-functionality of ecosystems and maximization of benefits both for humans and for natural conservation. First, they quantified and mapped the natural capacity to deliver ecosystem

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services and, second, they identified core habitats and wildlife corridors for biota. They applied the method at a continental scale, considering eight ecosystem services and the habitat requirements of large mammal populations. Arcidiacono et al. (2016) proposed a methodology for the spatial identification of the regional green infrastructure in the Lombardy Region of northern Italy. They selected two models from the InVEST software as a proxy of natural and recreational values and used the Kernel density (a geospatial analysis procedure) to develop visual elements as a proxy of landscape values. Snäll et al. (2016) outlined a toolbox of methods useful for green infrastructure design that explicitly accounts for biodiversity and ecosystem services, namely using spatial conservation prioritization and modeling of biodiversity features and ecosystem services.

Snäll et al. (2016) concluded that spatial conservation prioritization methods are effective tools for green infrastructure design. They also determined that sufficiently accurate spatial data at relevant resolutions are needed, especially for spatial data on ecosystem services and on the occurrence of multiple biodiversity features, such as species and habitat types. Small islands typically have limited human and economic resources (Mimura et al. 2007) to appropriately manage their resources and associated problems. The technical knowledge and geospatial data to successfully implement and develop spatial planning models are frequently unavailable. This is the case for municipalities in the Azores, a Portuguese archipelago in the North Atlantic Ocean.

Spatial planning in Portugal is a public policy expressed by the spatial organization of human activities and interests and the protection of natural resources (Calado et al. 2015). The Azores, an archipelago composed of nine small islands, is an autonomous region of Portugal and is one of the outermost regions of the EU. The Azorean Regional Government has political and administrative autonomy to create or adapt national legislation to region-specific interests, but they must also comply with or adapt to both European and Portuguese legislations.

The legal framework for territorial management in the Azores is currently established by the Regional Legislative Decree No. 35/2012/A of 2012 and is organized into two levels: regional and municipal. At the municipal level, Municipal Master Plans (MMPs) are tools for the socio-economic development of the municipalities and define a model of territorial organization, establishing parameters for occupation and land use. Each MMP must identify and map the systems for protecting the values of natural, cultural, agricultural and forest resources, thereby providing the delineation of municipal ESt (Regional Legislative Decree No. 35/2012/A of 2012). The mapping of ESt is, therefore, already required in the Azores for spatial planning, but no specific guidelines or standard methodologies have been provided to support municipalities in implementing the concept. This means that on islands with several municipalities, each municipality may choose a method to implement, regardless what neighboring municipalities choose. This can lead to discrepancies at the island level. Moreover, MMPs in Portugal should be revised every 10 years and some plans in the Azores are about to be revised. Municipalities will need to adopt a methodology, adapted to their unique data and technical resources, to design their ESt conforming, at the same time, with European and national guidelines and directives.

The ESt intends to maintain natural processes and the balance of healthy ecosystems, ensuring the preservation of their functions and services that ultimately enhance the quality of life for communities and people (e.g., Naumann et al. 2011; Regional Legislative Decree No. 35/2012/A of 2012; COM 2013). The European Commission (COM 2013) advocates that 'green infrastructure' (designated as an ESt in accordance with Portuguese legislation) requires a holistic view of ecosystem services. This provides an opportunity to improve decision-making by integrating ecological and sustainable goals into spatial planning, which will ultimately contribute to maintaining healthy ecosystems and their capacity to provide ecosystem services. Several EFs, which are the basis for the provision of ecosystem services, and resources are potentially more limited on confined territories than continental territories. Hansen and Pauleit (2014) demonstrated that ESt and ecosystem services 'are closely related and may strengthen each other in the development of a common framework for research as well as for implementation.' Thus, the incorporation of ESt into local and regional policies and its design based on EFs should be especially advantageous on small islands systems, such as the Azores.

Since the main concern of ESt is the maintenance of natural processes and the provision of ecosystem services, it is arguable that its delineation should be based on the identification and spatialization of EFs (Vergílio and Calado 2016). These authors discussed the integration of ESt into spatial planning on small islands, particularly the Azores archipelago, and proposed a theoretical framework to define ESt, which includes the requirements from Portuguese legislation and the identification of EFs that are consistent with European guidelines. According to these authors, ESt should be based on the territorial units (TUs) defined by environmental factors that characterize the territory of the entire island, for both ecosystem health and the provision of services. The second phase consists of: (i) identifying the areas that are legally subject to restrictions and constraints, defining the 'priority ESt' and ensuring that ESt complies with the island's environmental legal framework and (ii) identifying the several EFs that contribute to the goals of ESt for the remaining territory that will define the 'secondary ESt.' Secondary ESt is less sensitive than the 'priority ESt.' but requires careful analysis to determine whether to promote conservation or development and articulating the limits of each option. A final phase combines this information with a multi-criteria decision-making model to integrate public and/or stakeholders participation. The end result is an informed trade-off analysis between EFs and allowing the ESt for the entire island to be mapped.

It is assumed in this study that good provision of ecosystem services depends on healthy EFs (De Groot 1992), despite that the distinction between 'function,' 'service,' and 'benefit' is still being debated (De Groot et al. 2010). This study intends to operationalize the methodology proposed by Vergílio and Calado (2016) to identify and map EFs so they can be integrated in the design of the ESt to be used by small municipalities or territories lacking detailed data on biodiversity and individual studies on ecosystem functions and services. This approach presents an exploratory strategy to identify and map a higher number of EFs. Several studies, however, use very few ecosystem services (Egoh et al. 2008; Liquete et al. 2015; Maes et al. 2015; Arcidiacono et al. 2016) for integration into island spatial planning. This study develops a methodology to map EFs that will, along with the multicriteria decision-making, map secondary ESt, following the theoretical framework proposed by Vergílio and Calado (2016). Using Pico Island (in the Azores) as a case study and focusing on 15 EFs that will contribute to meet the objectives of ESt referred in the Azorean legislation, the study develops a practical methodology to aggregate and map EFs, using specific available studies on individual EFs or based on TUs' features. The extent to which Pico Island-protected areas (PAs) (Regional Legislative Decree No. 20/2008/A of 2008) and alternative or complementary areas relevant for the conservation of species on Pico Island (Vergílio, Fonseca, et al. 2016) overlap EFs is also assessed.

2. Conceptual framework

Natural capital has been widely used in the literature as a useful analogy for environmental resources and can be understood as 'any stock of natural resources or environmental assets, such as oceans, forests or agricultural land, that yield a flow of useful goods and services now and into the future' (MacDonald et al. 1999). Natural capital also often includes the capacity to assimilate waste (such as the capacity of the atmosphere to absorb pollution), life-support functions provided by the environment (such as the ozone layer) and the amenities of environmental resources (such as the aesthetic quality of landscapes) (Costanza et al. 1997; MacDonald et al. 1999).

The concepts of 'ecosystem function' and 'ecosystem services' have been defined, but there is some confusion over their distinction. The terms are sometimes used to describe the combination of processes and structures and the internal functioning of an ecosystem. They are also associated with human benefits that societies derive from the properties and processes of ecosystems, reflecting human demand and economic evaluation (De Groot et al. 2003, 2010). Definitions and classifications are still debated, which is not surprising given the myriad ways in which ecosystems support human life and contribute to its well-being ([TEEB] The Economics of Ecosystems and Biodiversity 2010).

In this study, the main difference between EFs and ecosystem services is articulated by De Groot et al. (2010): 'ecosystem services are generated by EFs which in turn are underpinned by biophysical structures and processes'. EFs are the biological, geochemical and physical processes and components of an ecosystem ([SEQ] Ecosystem Services Project 2016). Functions result from the natural processes of the ecological subsystem to which they belong, and they represent the potential to constitute direct and indirect sources of goods (e.g., provision of food; fuel and construction materials) and services (e.g., purification of air and water and generation and renewal of soil fertility) for human societies (De Groot et al. 2003; Song et al. 2016). Therefore, protecting EFs is fundamental to maintaining the supply of these services.

Using EFs in spatial planning and in the design of the ESt should allow spatial-planning tools (such as MMPs) to be as up to date as possible, avoiding the dependence of evaluations of ecosystem services on market prices or political will (Vergílio and Calado 2016).

Some EFs provided by natural capital are essential for maintaining their own balance, and others are essential for the persistence of goods and services that natural capital offers ([MEA] Millennium Ecosystem Assessment 2003). Ekins et al. (2003) suggest a distinction between 'functions of' the natural capital and 'functions for' humans provided by natural capital (Figure 1). 'Functions of' are defined from an ecological perspective, such as the basic processes and cycles of the internal functioning of natural systems that regulate the conditions of life and are responsible for sustaining and maintaining the stability and resilience of ecosystems resulting from the continuous interactions between biotic and abiotic components and their co-evolution (Holling et al. 1995; De Groot et al. 2003; Ekins et al. 2003). The

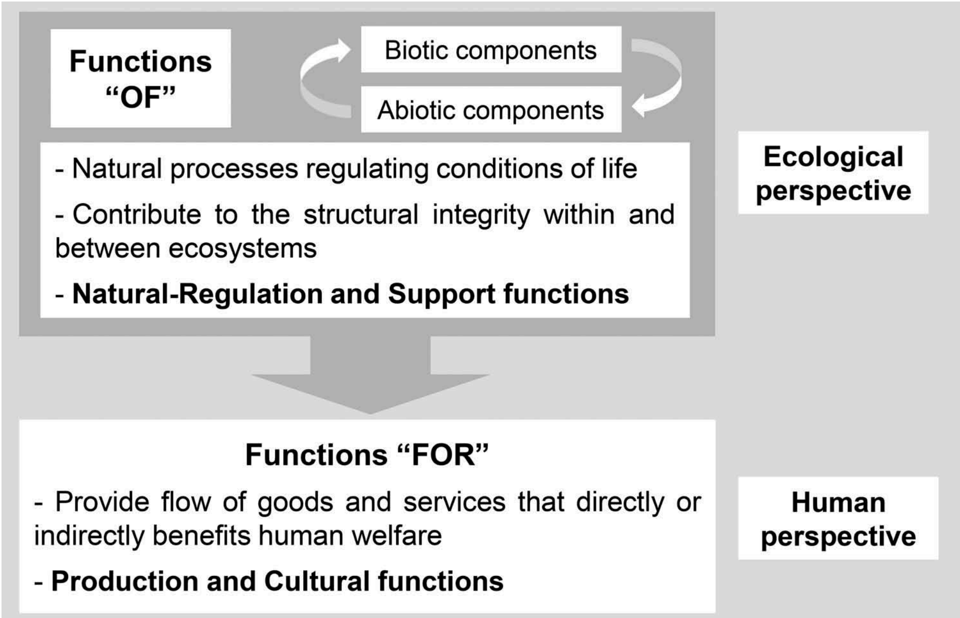

Figure 1. General classification of ecosystem functions (EFs) (De Groot et al. (2002) and Ekins et al. (2003)).

'functions for' are defined from a human perspective, in which the flow of natural or processed goods and services and the absorption of wastes from human activities directly or indirectly contribute to human well-being. In general, 'functions of' are the basis for the 'functions for', which could not be sustainable without natural capital (De Groot et al. 2003; Ekins et al. 2003).

The above categorization comprises one of the most common classifications of EFs (Costanza et al. 1997; De Groot 1992, 2006; De Groot et al. 2000, 2002; Oikonomou et al. 2011). It is sometimes also used as a classification for ecosystem services, such as De Groot et al. (2010), De Groot et al. (2012), [TEEB] The Economics of Ecosystems and Biodiversity (2010), MEA (2003), Kovács et al. (2015), Eastwood et al. (2016) and in the Portuguese legislation (Decree-Law No. 142/). 'Functions of' includes natural regulation and support functions, and 'functions for' includes production and cultural functions (De Groot et al. 2003; Ekins et al. 2003).

The natural regulation functions refer to the ability of natural and semi-natural ecosystems to regulate ecological processes that play a key role in maintaining the balance of the systems that support life, through biogeochemical cycles and other biospheric processes, and provide direct and indirect services to society (De Groot et al. 2002; [MEA] Millennium Ecosystem Assessment 2003). Support functions correspond to local landscapes, providing habitats (suitable living space), refugia and breeding and nursery grounds for wild plants and animals and contributing to the *in situ* conservation of biological and genetic diversity and evolutionary processes (De Groot et al. 2002; [SEQ] Ecosystem Services Project 2016). Production functions are associated with processes that allow the provision of natural resources, goods and services for human consumption (De Groot et al. 2002; [SEQ] Ecosystem Services Project 2016). Cultural functions are those providing intangible benefits by the exposure to life processes and natural systems (De Groot et al. 2002; [MEA] Millennium Ecosystem Assessment 2003; [SEQ] Ecosystem Services Project 2016).

EFs, and not ecosystem services, are used in this study as the basis of a strategic approach to integrate the design of the ESt, assuming that ensuring well-functioning ecosystems produces good conditions for providing ecosystem services in the future.

3. Methodology

3.1. Study area

The study was carried out in the Azores archipelago, located in the North Atlantic between 37 and 40°N and 25 and 31°W, approximately 1500 km from the Portuguese mainland and 3900 km from the east coast of North America (Figure 2). The islands are geographically divided into three groups: Western Group (Flores and Corvo), Central Group (Graciosa, São Jorge, Faial, Pico and Terceira) and Eastern Group (São Miguel and Santa Maria).

The Azores have a temperate oceanic climate with a mean annual temperature of 17°C at sea level, low thermal amplitude, high mean relative humidity, persistent wind and rainfall ranging from 800 to 3000 mm/m^2 which increases with altitude (Azevedo 1996). The Azores are characterized by low and rocky coastlines and coastal cliffs (Borges 2003), prominent

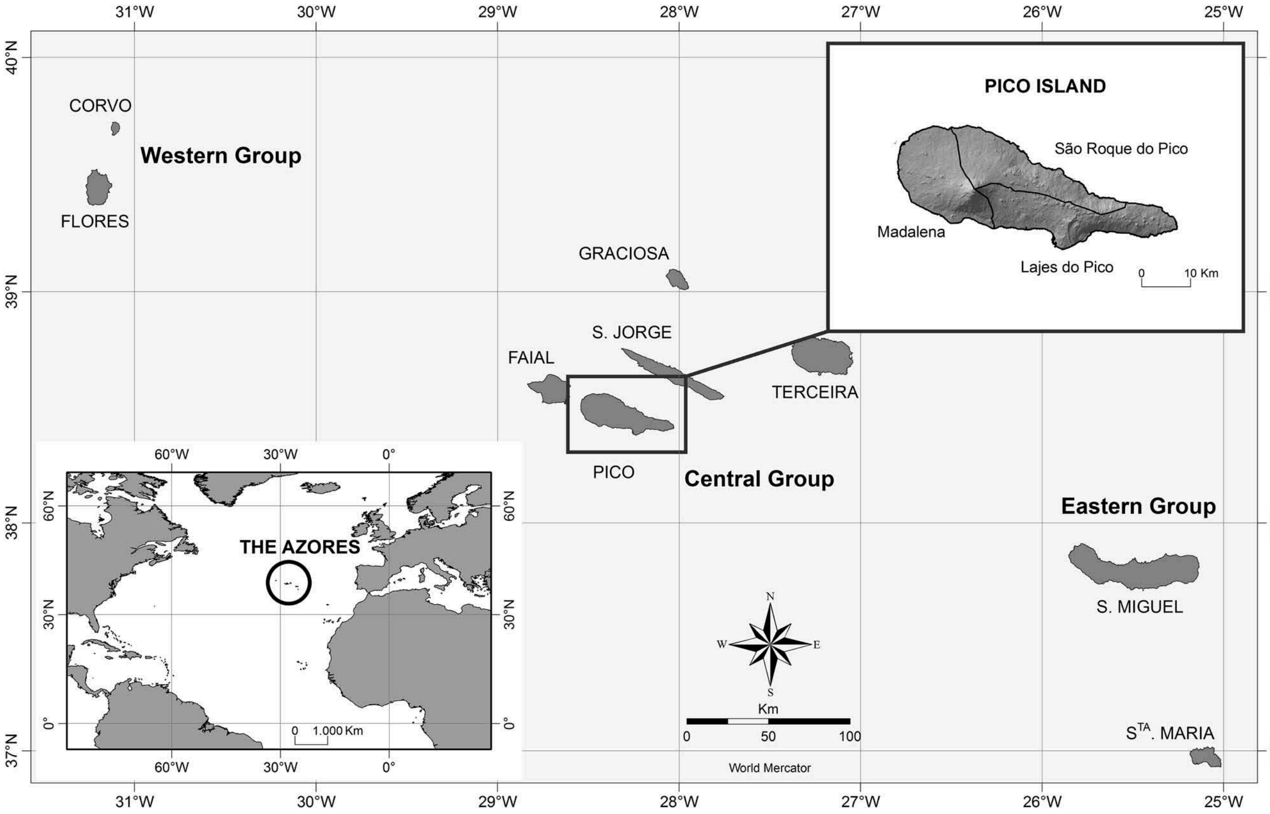

Figure 2. Location of the Azores archipelago (Portugal) and Pico Island (municipality administrative boundaries).

river valleys in eroded volcanic rocks, vast lava flows and active volcanoes (Condé and Richard 2002). The association between the physiographic and climatic regime contributes to the low diversity of water resources (ephemeral and torrential streams, lagoons, small ponds, coastal waters and groundwater) and small watersheds (usually <30 km^2) ([DROTRH/IA] Direcção Regional do Ordenamento do Território e dos Recursos Hídricos/Secretaria Regional do Ambiente 2001). Located near the triple junction of the American, Eurasian and African plates (Cruz 2003), the Azores are highly vulnerable to tsunamis, seismic or volcanic events and landslides (Andrade et al. 2006). The archipelago is part of the Macaronesia Biogeographic Region, along with the Madeira archipelago (Portugal), Canary Islands (Spain) and Cape Verde, and is one of Europe's unique areas of biodiversity (Condé and Richard 2002).

This study focused on Pico Island (Figure 2), the youngest and second largest Azorean island, covering an area of 447 km^2, with 152 km of coastline and reaching an elevation of 2351 m at the top of its volcano, Mount Pico, in the western part of the island. Pico Island is divided into three municipalities: Madalena, São Roque do Pico and Lajes do Pico, with a population density of approximately 31.8 inhabitants/km^2 in 2011 (PORDATA 2015). The economy is currently dependent mainly on crops, cattle production, fisheries and tourism (Calado et al. 2014). Settlements, transportation infrastructure and economic activities are concentrated along the coast, mainly due to their dependence on the sea as the most important route of commerce and to the geological, geomorphologic and climatic constraints of the island (Porteiro et al. 2005). Forests include stands of *Cryptomeria japonica* and *Eucalyptus globulus*. Agricultural areas include a traditional viticulture with a strong sociocultural identity classified as a UNESCO world heritage site – Landscape of the Pico Island Vineyard Culture – and grasslands. The center of the island is dominated by large grasslands and natural areas, such as wetlands, peat bogs and several types of native forest and shrubland (Costa et al. 2013), containing the majority of the PAs (Figure A1 in Appendix A). The development of monocultural landscapes for pastures and forests increased the fragmentation of the natural ecosystems and changed the biodiversity in Pico and many areas of the archipelago, giving rise to the expansion of non-indigenous and invasive species (Silva and Smith 2006) and greater homogenization of ecological communities (Florencio et al. 2013).

Pico's Island Natural Park (INP) contains 22 PAs (Figure A1, Appendix A) (19 terrestrial and 3 marine): four nature reserves, one natural monument, eight PAs for habitat/species management, six protected landscapes and three PAs for resource management (all three are coastal and marine areas).

Pico Island was chosen as a case study because it has the largest proportion of PAs (approximately 35%

of the island territory), several activities occur across the island and the three MMPs will be soon under revision. ESt is an element of the MMPs, so developing a methodology for Pico Island may be useful for integrating the revised plans in the future.

3.2. Selection of EFs

To identify and map EFs to be integrated in the ESt, the first step was the selection of EFs that contribute to achieve ESt objectives (Figure 3(a)). A revision of the literature on EFs and ecosystem services was performed (De Groot 1992, 2006; Costanza et al. 1997; De Groot et al. 2000, 2002, 2010, 2012; [MEA] Millennium Ecosystem Assessment 2003, 2005; [TEEB] The Economics of Ecosystems and Biodiversity 2010; Eastwood et al. 2016) in order to identify the EFs' classifications that are most accepted in the scientific community. Priority was given to classifications that specifically categorize EFs. Remaining literature was also used to identify gaps on previous papers and the missing ecosystem services were converted into EFs (e.g., the ecosystem service 'genetic resources,' identified in [MEA] Millennium Ecosystem Assessment (2003), can be converted to the EFs 'maintenance of natural evolutionary processes').

The classification used in the present methodology was mainly based on those proposed by Costanza et al. (1997) and De Groot et al. (2002, 2010). Considering the particular case study of Pico Island, the ESt should identify systems for the protection of natural, cultural, agricultural and forest resources (Regional Legislative Decree No. 35/2012/A), thus only EFs associated with these resources were selected (Table 1).

The selection of functions also considered the insular context. For example, small islands have insufficient area to contribute much to the regulation of the global climate, so this function (Eastwood et al. 2016) and the chemical regulation of the atmosphere (De Groot 1992) were adapted to represent the function at the local scale. Small islands may contribute little to global climate change but are highly exposed and susceptible to its consequences, namely coastal storms and landslides (Nurse et al. 2014). Coastal hazards are a major issue in these territories, so the mitigation of extreme coastal events was added as an EF, even though it is not an intrinsic function of the ecosystem itself. The chemical regulation of the local atmosphere was evaluated separately from carbon storage based on Vergílio, Fjøsne, et al. (2016). It is assumed that the regulation of the local atmosphere contributes to the release of gases to the atmosphere (mainly carbon dioxide) and carbon storage sequesters carbon from the atmosphere.

3.3. Description of data

This methodology includes two approaches for which a schematic representation is given in Figure 3.

The first approach assumed that studies focused on mapping individual EFs in the study area are as accurate as possible (Figure 3(b)). Geospatial data resulting from those studies were used to map corresponding EFs if they existed in the available literature and/or digital databases at appropriate scale and format. Individual studies were used to map the functions of carbon storage (Vergílio, Fjøsne, et al. 2016) and groundwater recharge (Cruz et al. 2011).

Several authors have advocated that planning decisions should be based on 'conserving the arenas, not the actors' (Beier and Brost 2010), that is, conserving geophysical features that contain diverse or important plant and animal assemblages, because climate change will change ecological communities (Ruddock et al. 2013). Beier and Brost (2010) advocated the use of land facets (recurring landscape units with identical topographic and soil attributes) when designing reserves for a changing climate, instead of climatic modeling or approaches based on mapped species ranges. The second approach assumed that EFs depend on natural processes and the interactions between biotic and abiotic elements and that integrating stable biophysical characteristics with land cover allow a complete analysis of the landscape, when data for individual EFs were not available (Figure 3(d)). TUs were defined to be the basis of mapping remaining EFs (Figure 3(c)), according to the following rationale.

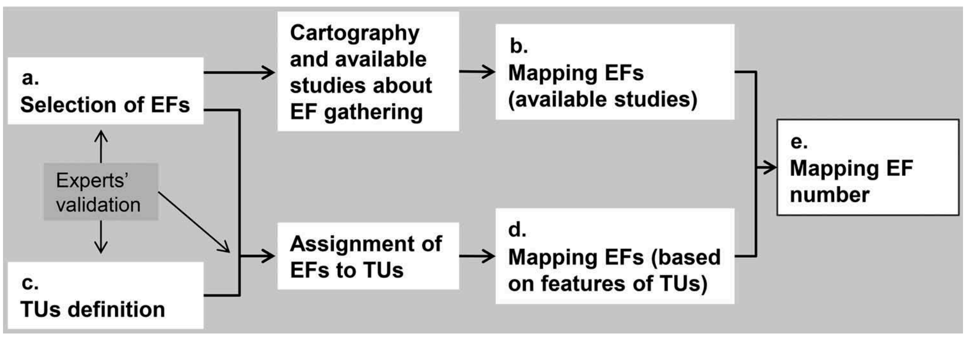

Figure 3. Representation of the proposed methodology to map several EFs (EF, ecosystem function; TUs, territorial units).

Table 1. Ecosystem functions (EFs) contributing to ecological structure objectives.

Natural regulation functions		Capacity of ecosystems to regulate natural ecological processes and the systems that support life on Earth, through biogeochemical cycles and other processes of the biosphere
1	Local climatic regulation	Role of ecosystems (e.g., influence of land cover) in regulating temperature, rainfall and other climatic processes at the local level
2	Chemical regulation of the local atmosphere	Role of ecosystems in the regulation of atmospheric chemical composition (e.g., balance between O_2 and CO_2 and other greenhouse gases). Carbon storage was considered for a particular function
2.1	Carbon storage	Role of ecosystems in carbon storage
3	Nutrient regulation and maintenance of soil fertility	Role of natural processes in the storage and cycling of nutrients and maintaining soil fertility
4	Soil formation	Role of ecosystems in organic material accumulation, chemical weathering of rocks and soil formation and regeneration
5	Soil retention	Role of ecosystems (e.g., vegetation root matrix and soil biota) in soil retention to prevent erosion and landslides
6	Mitigation of extreme coastal events	Influence of terrestrial ecosystems in dampening extreme coastal events (e.g., coastal flooding, winds, and sea spray)
7	Regulation of flow of inland waters	Influence of terrestrial ecosystems, topography, soils and hydrological conditions on the spatial and temporal distribution of inland waters, regulating flow and contributing to flood prevention
8	Surface-water catchment	Role of ecosystems in capturing and retaining surface water (natural reservoirs)
9	Groundwater recharge	Role of ecosystems in water infiltration and aquifer recharge
Support functions		Local habitats providing species occurrence, refugia and breeding and nursery grounds for plants and animals, and ecosystems contributing to biological conservation and the preservation of genetic diversity and natural evolutionary processes
10	Local habitats	Natural and semi-natural ecosystems providing habitat for resident species important for conservation
11	Refugium and nursery	Ecosystems providing refugia and suitable places for feeding, breeding and raising young for transient species
12	Maintenance of natural evolutionary processes	Contribution of natural ecosystems to maintaining natural evolutionary processes and preserving native biological and genetic diversity
Cultural functions		Capacity of ecosystems to provide intangible benefits, such as landscape aesthetic value, artistic and spiritual inspiration, historical and educational values and the 'sense of place'
13	Landscape attractiveness	Landscapes with attractive features, with aesthetic qualities based on, for example, structural diversity, quiet and 'greenness'
14	Cultural heritage	Role of ecosystems to cultural facets with historical value, providing opportunities for non-commercial uses

Costanza et al. (1997) and De Groot et al. (2002, 2010).

3.3.1 TUs' definition

Landscapes may be characterized for planning purposes by stable biophysical characteristics and related functions and processes and by manageable land-use patterns and related functions and processes (Fernandes et al. 2014). Ruddock et al. (2013) mapped ecological land units (relatively homogeneous associations of landforms and geomorphologic compositions) based on data for landform, soil drainage and surface texture, and open water. Fernandes et al. (2014) mapped ecological reference units (ERUs) (combinations of stable biophysical variables defining a homogeneous reference system) based on geology, morphology, soil potential productivity, climate, internal drainage areas and their respective watersheds and ravines and similar water courses.

The ERUs proposed by Fernandes et al. (2014) and the land covers proposed by Moreira (2013, unpublished data) were combined to define the TUs for Pico Island (Table 2). These two layers were overlaid using ArcGIS (version 10.3) 'union' and 'dissolve' tools, to obtain one map with the TUs (Figure B1, Appendix B). The selection of features (morphoclimatic, soil, land cover, or others) to define TUs is dependent on the study site, on available geospatial data and on the level of detail to be represented in each TU, which can be adapted to other contexts.

This study was exploratory with the objective of developing a practical methodology, so ERUs and land covers were simplified to decrease the final number of TUs. Morphoclimatic features depending on climatic variables (precipitation, humidity and wind) were grouped to form a middle zone around the island: a ring between Mount Pico and the remaining areas closer to the coast (Table 2). Land cover is also influenced by geology, so the geological types from Fernandes et al. (2014) were not used in the present study, avoiding redundancy and decreasing the number of TUs.

A soil map is not available for Pico Island, only the Soil Quality Map (Pinheiro et al. 1987, unpublished data) which represents the suitability of soils for agriculture, classed on a scale of I–VII, and referencing particular limiting factors (soil subclasses), such as risk of erosion or limitation of the rooting zone. Pico Island lacks classes I and II, the most suitable for agriculture. The selected EFs already comprised functions protecting agriculture, so only soil subclasses were used to define TUs.

Some of the land covers from Moreira (2013, unpublished data) were also aggregated following the same rationale for simplification. Areas covered by exotic forest species were merged, despite having distinct behaviors and different economic objectives. Endemic macaronesian heath and areas of *Myrica faya* were also combined, because they are mainly native species.

3.4. Exploratory data analysis and mapping EFs

At this point, EFs for which we had existing geospatial data were mapped and it was necessary to map the remaining EFs.

Table 2. Stable biophysical features and land-cover classes used to define territorial units (TUs).

Morphoclimatic features (adapted from Fernandes et al. (2014))	
Escarpments and cliffs	A narrow strip along the coast, mainly rocky
Coastal areas	Coastal areas inland from escarpments and cliffs, generally reaching 30 or 40 m in altitude
Transitional zones and lowlands	Strip immediately inland from the coastal areas, generally between 30–40 and 200 m
Middle zone	Strip immediately inland from the transitional zones to the base of Mount Pico, generally between 200 and 1100 m
Lagoons	Lagoons
Peat bogs	Peat bogs
Valleys	Narrow valleys generally with non-permanent and torrential streams
Marshes	Marshes are mainly located along the middle zone, following the distribution of lagoons; a few marshes are also located in the transitional zones and lowlands
Mount Pico	Mount Pico, above 1100 m
Soil subclasses (from the use-capacity map of Pinheiro et al. (1987, unpublished data))	
-	Without limitations
w	Soils for which excess water is the dominant hazard or limitation affecting their use (e.g., drenching)
e	Soils for which the susceptibility to erosion is the dominant problem or hazard affecting their use
s	Soils that have limitations within the rooting zone (e.g., shallowness of the rooting zone, stones, low moisture-holding capacity, low fertility that is difficult to correct and high salinity or sodium content)
e, s	Soils with high susceptibility to erosion and limitations within the rooting zone
Land cover (adapted from Moreira (2013, unpublished data))	
Urban	Urban areas and roads
Agriculture	Areas covered with crops
Vineyards	Areas covered with vineyards
Grasslands	Intensive and semi-natural grasslands
Forests	Areas covered with exotic forest species for production (*C. japonica*, *E. globulus* and *Pinus pinaster*) and with mainly exotic species with invasive character (*Pittosporum undulatum* and *Acacia melanoxylon*)
Rocky shore	Rocky shoreline
Bare soil	Open spaces without vegetation
Waterbodies	Lagoons and other natural waterbodies
Alpine and boreal heath	Areas covered with natural vegetation adapted to higher altitudes in the crater and on the mountain
Peat bogs	Peat bogs
Natural vegetation	Areas covered with natural vegetation, mainly native species, including endemic macaronesian heath and areas of *M. faya*

TUs were used as cartographic units to assign each remaining EF (Figure 3(d)). Having in consideration the set of selected features to define TUs and the characteristics of each TU, each EF was identified and assigned as present or absent in each TU (Table 3). A value of 0 is assigned if the EF is absent and a value of 1 is assigned if the EF is present. The table resulting from this procedure, with all EFs assigned to all TUs, was used to join to the TUs shapefile (Figure 3(e)). This allows integrating several EFs resulting in one shapefile that includes all the information in each polygon (morphoclimatic features, soil subclasses, land cover and EFs).

Several assessments were possible with this information. For this study, four maps were created (Figure 4), one with the total number of EFs and one with total number of EFs in each main category of EFs (natural regulation, support and cultural functions). All cartographic operations and analyses were performed using ArcGIS software (version 10.3).

Vergílio, Fonseca, et al. (2016) analyzed the efficiency of current PAs for meeting individual conservation targets (based on the context of each species in the archipelago and its current conservation status) and identified alternative or complementary areas relevant for the conservation of species on Pico Island. These areas were ranked in four quartiles. The quartile with the highest value for conservation was used to overlay the map with the total number of EFs in order to analyze to what extent these areas overlap a high number of EFs. A similar procedure and analysis was used with existing PAs to overlay the map with the total number of EFs.

3.5. Validation

The value of integrating experts' opinion into spatial planning (Knight et al. 2006; Lehtomäki and Moilanen 2013), including in the design of ESt (Snäll et al. 2016), is widely recognized. In this study, experts were queried also to avoid personal biases.

Local experts were asked to contribute their deep knowledge on the Azores and, specifically in Pico Island, to validate different steps of the methodology (Figure 3). Firstly, they were asked to validate the selection of EFs and to identify if any were not logical and appropriate, or if any were missing given the objectives of the ESt. Secondly, they were asked to validate TUs, namely the adopted aggregation process to decrease number of TUs. Finally, experts were asked to validate the assignment of each EFs to each TU. The expert input was obtained through individual interviews. Final decisions and outputs were made according to the majority if no consensus existed among the interviewees.

Selected experts were researchers working specifically in the Azores archipelago with knowledge of the scientific issues of each EF (e.g., volcanology and geology, hydrological resources, soils, biodiversity

Table 3. EFs assigned to each TU: 1, each function present in each TU; 0, absence of the function in each TU.

				Natural regulation functions										Support functions			Cultural functions	
Morphoclimatic features	Soil subclass	Land cover	TU code	EF1	EF2	EF2-1	EF3	EF4	EF5	EF6	EF7	EF8	EF9	EF10	EF11	EF12	EF13	EF14
Escarpments and cliffs	-	Urban	1	0	0	0	0	0	0	0	0	0	*	0	0	0	1	1
	-	Forests	2	1	1	1	1	1	1	1	0	0	*	1	0	0	1	0
	-	Agriculture	3	0	0	0	1	0	0	1	0	0	*	0	1	0	1	0
	-	Grasslands	4	0	1	0	1	0	0	1	0	0	*	0	0	0	1	0
	-	Bare soil	5	0	1	0	0	0	0	1	0	0	*	1	1	0	1	0
	-	Rocky shore	6	0	0	0	0	0	0	1	0	0	*	1	1	0	1	0
	-	Natural vegetation	7	1	1	1	1	1	1	1	0	0	*	1	1	1	1	0
	-	Vineyards	8	0	0	1	1	0	1	1	0	0	*	0	1	0	1	1
	e	Rocky shore	9	0	0	0	0	0	0	1	0	0	*	1	1	0	1	0
Coastal areas	-	Urban	10	0	0	0	0	0	0	1	0	0	*	0	0	0	1	1
	-	Forests	11	1	1	1	1	1	1	1	1	0	*	1	0	0	1	0
	-	Agriculture	12	0	0	0	1	0	0	1	0	0	*	0	1	0	1	0
	-	Grasslands	13	0	1	0	1	0	0	0	1	0	*	0	0	0	1	0
	-	Bare soil	14	0	1	0	0	0	0	0	0	0	*	1	1	0	1	0
	-	Natural vegetation	15	1	1	1	1	1	1	1	1	0	*	1	1	1	1	0
	-	Vineyards	16	0	0	1	1	0	1	1	1	0	*	0	1	0	1	1
	e	Forests	17	1	1	1	1	1	0	1	1	0	*	1	0	0	1	0
	e	Bare soil	18	0	1	0	0	0	0	0	0	0	*	1	1	0	1	0
Transitional zones and lowlands	-	Urban	19	0	0	0	0	0	0	1	0	1	*	0	0	0	1	1
	-	Forests	20	1	1	1	1	1	1	1	1	1	*	1	0	0	1	0
	-	Agriculture	21	0	0	0	1	0	0	0	0	0	*	0	1	0	1	0
	-	Grasslands	22	0	1	0	1	0	0	0	1	1	*	0	0	0	1	0
	-	Bare soil	23	0	1	0	0	0	0	0	0	0	*	0	0	0	1	0
	-	Rocky shore	24	0	0	0	0	1	0	0	0	0	*	0	0	0	1	0
	-	Natural vegetation	25	1	1	1	1	1	1	1	1	1	*	1	1	1	1	0
	-	Vineyards	26	0	0	1	1	0	1	1	1	0	*	0	1	0	1	1
Middle zone	-	Urban	27	0	0	0	0	0	0	NA	0	1	*	0	0	0	1	0
	-	Forests	28	1	1	1	1	1	1	NA	1	1	*	1	1	0	1	0
	-	Agriculture	29	0	0	0	1	0	0	NA	0	0	*	0	1	0	1	0
	-	Grasslands	30	0	1	0	1	1	1	NA	1	1	*	1	1	0	1	0
	-	Bare soil	31	0	1	0	0	0	0	NA	0	0	*	1	0	0	1	0
	-	Rocky shore	32	0	0	0	0	1	0	NA	0	0	*	1	0	0	1	0
	-	Natural vegetation	33	1	1	1	1	1	1	NA	1	1	*	1	1	1	1	0
	-	Vineyards	34	0	0	1	1	0	1	NA	1	0	*	0	1	0	1	1
	e	Urban	35	0	0	0	0	0	0	NA	0	1	*	0	0	0	1	0
	e	Forests	36	1	1	1	1	1	0	NA	1	1	*	1	1	0	1	0
	e	Agriculture	37	0	0	0	1	0	0	NA	0	0	*	0	1	0	1	0
	e	Grasslands	38	0	1	0	1	1	0	NA	1	1	*	1	1	0	1	0
	e	Waterbodies	39	1	0	0	0	0	0	NA	1	1	*	1	1	1	1	0
	e	Bare soil	40	0	1	0	0	0	0	NA	0	0	*	1	0	0	1	0
	e	Peat bogs	41	1	0	1	1	1	1	NA	1	1	*	1	1	1	1	0
	e	Natural vegetation	42	1	1	1	1	1	1	NA	1	1	*	1	1	1	1	0
	e, s	Natural vegetation	43	1	1	1	1	1	1	NA	1	1	*	1	1	1	1	0
	s	Forests	44	1	1	1	1	1	0	NA	1	1	*	1	1	0	1	0
	s	Grasslands	45	0	1	0	1	1	0	NA	1	1	*	1	1	0	1	0
	s	Natural vegetation	46	1	1	1	1	1	1	NA	1	1	*	1	1	1	1	0
Lagoons	w	Waterbodies	47	1	0	0	0	0	0	NA	1	1	*	1	1	1	1	0
	e	Waterbodies	48	1	0	0	0	0	0	NA	1	1	*	1	1	1	1	0
Peat bogs	e	Grasslands	49	0	1	0	1	1	0	NA	1	1	*	1	1	0	1	0
	e	Peat bogs	50	1	0	1	1	1	1	NA	1	1	*	1	1	1	1	0
Valleys	-	Urban	51	0	0	0	0	0	0	NA	0	1	*	0	0	0	1	0
	-	Forests	52	1	1	1	1	1	1	NA	1	1	*	1	0	0	1	0
	-	Agriculture	53	0	0	0	1	0	0	NA	0	0	*	0	1	0	1	0
	-	Grasslands	54	0	1	0	1	0	0	NA	1	1	*	0	0	0	1	0
	-	Bare soil	55	0	1	0	0	0	0	NA	0	0	*	1	0	0	1	0
	-	Rocky shore	56	0	0	0	0	1	0	NA	0	0	*	1	0	0	1	0
	-	Natural vegetation	57	1	1	1	1	1	1	NA	1	1	*	1	1	1	1	0
	-	Vineyards	58	0	0	1	1	0	0	NA	1	0	*	0	1	0	1	1
	e	Forests	59	1	1	1	1	1	0	NA	1	1	*	1	0	0	1	0
	e	Bare soil	60	0	1	0	0	0	0	NA	0	0	*	1	0	0	1	0
	e	Natural vegetation	61	1	1	1	1	1	1	NA	1	1	*	1	1	1	1	0

(*Continued*)

Table 3. (Continued).

Morphoclimatic features	Soil subclass	Land cover	TU code	Natural regulation functions										Support functions			Cultural functions	
				EF1	EF2	EF2-1	EF3	EF4	EF5	EF6	EF7	EF8	EF9	EF10	EF11	EF12	EF13	EF14
Marshes	-	Urban	62	0	0	0	0	0	0	NA	0	1	*	0	0	0	1	0
	-	Forests	63	1	0	1	1	1	1	NA	1	1	*	1	1	0	1	0
	-	Agriculture	64	0	0	0	1	0	0	NA	0	0	*	0	1	0	1	0
	-	Grasslands	65	0	0	0	1	1	1	NA	1	1	*	1	1	0	1	0
	-	Waterbodies	66	1	0	0	1	1	0	NA	1	1	*	1	1	1	1	0
	-	Bare soil	67	0	0	0	0	0	0	NA	0	0	*	1	0	0	1	0
	-	Peat bogs	68	1	0	1	1	1	1	NA	1	1	*	1	1	1	1	0
	-	Natural vegetation	69	1	0	1	1	1	1	NA	1	1	*	1	1	1	1	0
	-	Vineyards	70	0	0	1	1	0	1	NA	1	0	*	0	1	0	1	1
	e	Forests	71	1	0	1	1	1	0	NA	1	1	*	1	1	0	1	0
	e	Grasslands	72	0	0	0	1	1	0	NA	1	1	*	1	1	0	1	0
	e	Waterbodies	73	1	0	0	1	1	0	NA	1	1	*	1	1	1	1	0
	e	Bare soil	74	0	0	0	0	0	0	NA	0	0	*	1	0	0	1	0
	e	Peat bogs	75	1	0	1	1	1	1	NA	1	1	*	1	1	1	1	0
	e	Natural vegetation	76	1	0	1	1	1	1	NA	1	1	*	1	1	1	1	0
	s	Grasslands	77	0	0	0	1	1	0	NA	1	1	*	1	1	0	1	0
	s	Natural vegetation	78	1	0	1	1	1	1	NA	1	1	*	1	1	1	1	0
Mount Pico	-	Alpine and boreal heath	79	1	0	0	1	1	1	NA	1	1	*	1	1	1	1	0
	-	Bare soil	80	1	1	0	0	0	0	NA	0	0	*	1	0	0	1	0
	e	Grasslands	81	1	1	0	1	1	0	NA	1	1	*	1	1	0	1	0
	e	Bare soil	82	1	1	0	0	0	0	NA	0	0	*	1	0	0	1	0
	e	Natural vegetation	83	1	1	1	1	1	1	NA	1	1	*	1	1	1	1	0
	e, s	Alpine and boreal heath	84	1	0	0	1	1	0	NA	1	1	*	1	1	1	1	0
	e, s	Bare soil	85	1	1	0	0	0	0	NA	0	0	*	1	0	0	1	0
	s	Grasslands	86	1	1	0	1	1	0	NA	1	1	*	1	1	0	1	0

-: without limitations; e: soils with high susceptibility to erosion; s: soil limitations in the rooting zone; w: soil with excess water (drenching); TU: territorial unit; EF1: local climatic regulation; EF2: chemical regulation of the local atmosphere; EF2-1: carbon storage; EF3: nutrient regulation and maintenance of soil fertility; EF4: soil formation; EF5: soil retention; EF6: mitigation of extreme coastal events; EF7: regulation of flow of inland waters; EF8: surface-water catchment; EF9: groundwater recharge; EF10: local habitats; EF11: refugia and nurseries; EF12: maintenance of natural evolutionary processes; EF13: landscape attractiveness; EF14: cultural heritage; NA: not applicable; *: geographic data adapted from Cruz et al. (2011)

and spatial planning). Approximately the same number of experts (2–3) was consulted for each scientific issue, and most opinions were consensual.

4. Results

4.1. Mapping EFs

The combination of the morphoclimatic features, soil subclasses and land covers on Pico Island produced 86 TUs (Table 3; see Appendix B for Figure B1 and more details). The assignment of EFs to each TU, after validation by experts, is summarized in Table 3.

Local climatic regulation (EF1) was assigned to Mount Pico as one main element of relief on the island contributing to the climatic conditions. Other elements (e.g., waterbodies, peat bogs and well-developed vegetation) were also assigned to EF1 because they contribute to the local climatic conditions such as temperature and humidity balance.

Raich and Potter (1995) estimated that the annual flux of carbon dioxide (CO_2) from soils to the atmosphere was larger than terrestrial net primary productivity. The rates of soil CO_2 efflux are generally lower from wetlands than from better drained sites, because high moisture levels inhibit aerobic respiration. Raich and Potter (1995) also reported that CO_2 emissions did not differ significantly between broadleaved and coniferous trees. Highly disturbed areas have lower rates of soil CO_2 efflux. The function of the chemical regulation of the local atmosphere (EF2) was thus assigned to grasslands (including emissions from cattle), forests and areas of natural vegetation and bare soil, except those in wetlands (such as peat bogs and marshes).

The carbon-storage function (EF2-1) was assigned to the areas with higher amounts of carbon storage based on the data reported by Vergílio, Fjøsne, et al. (2016): vineyards, forests, peat bogs and areas of natural vegetation. Grasslands and agricultural land were not assigned to EF2-1 due to less carbon storage and the frequent rotation of crops and removal of biomass.

The function of nutrient regulation and maintenance of soil fertility (EF3) was assigned to agricultural land (artificial input from fertilizers), vineyards, grasslands, forests, areas with alpine and boreal heath, peat bogs and areas of natural vegetation. This function was also assigned to waterbodies in marshes due to the seasonal drenching that releases nutrients.

Soil formation (EF4) was generally assigned to forests, areas with alpine and boreal heath, peat bogs and areas of natural vegetation. This function

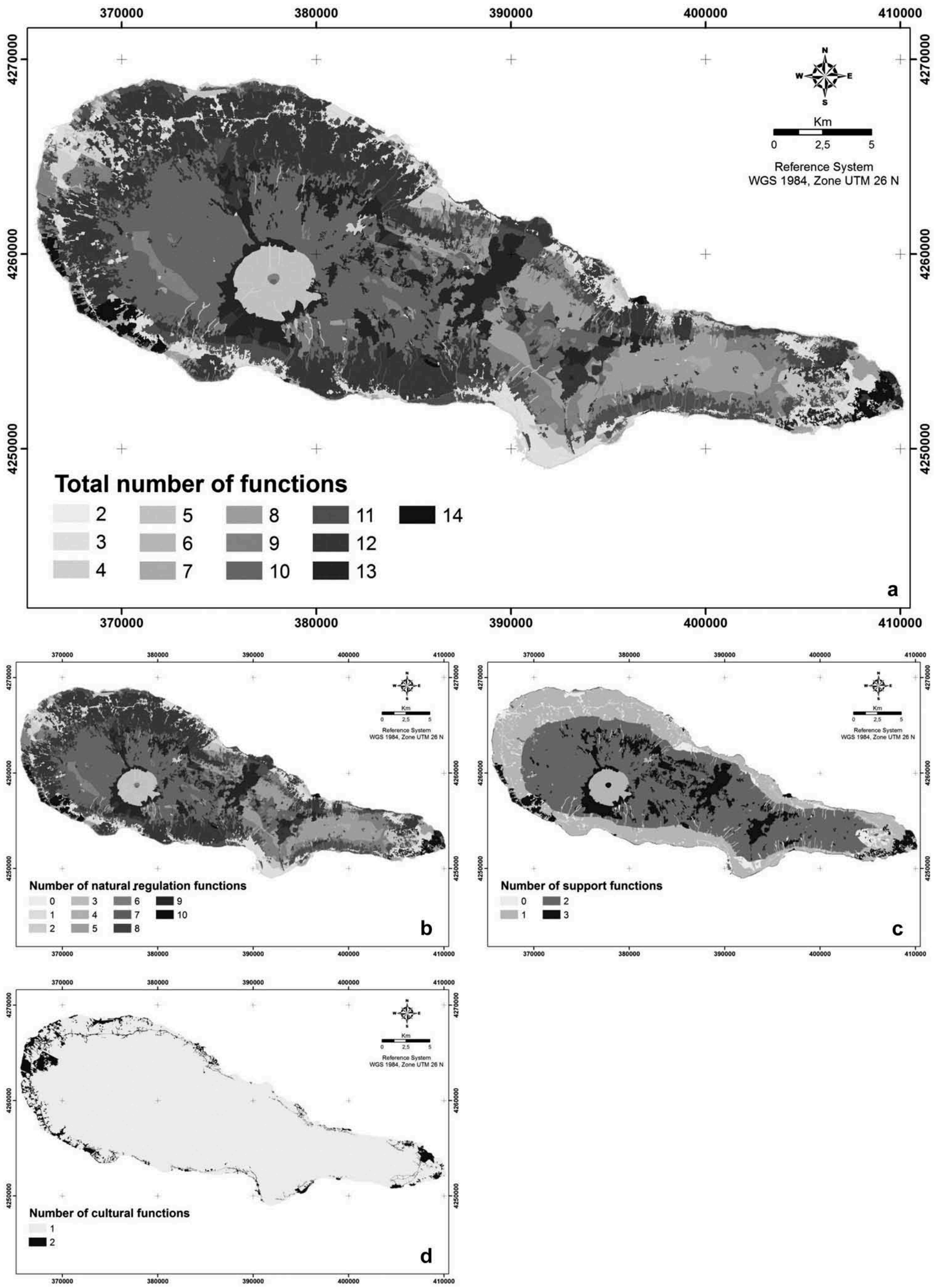

Figure 4. Number of overlapping functions on Pico Island: (a) total number of functions; (b) number of natural regulation functions; (c) number of support functions; and (d) number of cultural functions.

was also assigned to waterbodies in marshes due to the seasonal drenching that contributes to soil formation; to rocky shores in transitional zones and lowlands, in the middle zone, valleys and marshes; and to grasslands on Mount Pico, in the middle zone, peat bogs and marshes, because the grasslands in these areas are usually permanent or semi-natural with less human intervention.

Soil retention (EF5) was generally assigned to peat bogs and areas of natural vegetation because these areas usually have dense and continuous soil cover with well-developed herbaceous and/or arbustive substrates. When soil subclasses had no limitations, this function was also assigned to vineyards on escarpments and cliffs and in coastal areas, marshes and transitional zones and lowlands; to areas with alpine and boreal heath; to forests and to grasslands at higher altitudes (middle zone, marshes and Mount Pico), because these areas usually contain semi-natural grasslands with less human intervention.

The mitigation of extreme coastal events (EF6) was only assigned to areas at lower altitudes: escarpments and cliffs, coastal areas and transitional zones and lowlands. Escarpments and cliffs were included regardless of land cover (except for urban areas), because these areas are obstacles to direct waves. Coastal areas included urban centers, agricultural land, vineyards, forests and areas of natural vegetation. Transitional zones and lowlands included urban centers, vineyards, forests and areas of natural vegetation, because these land covers contribute to the mitigation of, for example, sea spray and winds.

The regulation of the flow of inland waters (EF7) was generally assigned to vineyards (due to the stone walls that slow water runoff), grasslands, forests, lagoons and other waterbodies, areas with alpine and boreal heath, peat bogs and areas of natural vegetation.

The function of surface-water catchment (EF8) was assigned to the areas contributing to the retention of water for natural availability: grasslands, forests, lagoons and other waterbodies, areas with alpine and boreal heath, peat bogs and areas of natural vegetation, except on escarpments and cliffs and in coastal areas.

The function of groundwater recharge (EF9) was mapped based on the data reported by Cruz et al. (2011), and value '1′ was assigned to polygons where the function was present.

The function of local habitats (EF10) was assigned to areas containing native species. These areas generally included forests, lagoons and other waterbodies, areas with alpine and boreal heath, peat bogs and areas of natural vegetation. This function was also assigned to rocky shores and areas of bare soil on escarpments and cliffs and in coastal areas (containing, e.g., marine species) on Mount Pico (where smaller species may be found, such as mosses and fungi) and in the middle zone, valleys and marshes; and to grasslands at higher altitudes in the middle zone and marshes and on Mount Pico, because these grasslands are usually semi-natural with less human intervention.

The function of refugia and nurseries (EF11) was generally assigned to agricultural land, vineyards, lagoons and other waterbodies, areas with alpine and boreal heath, peat bogs and areas of natural vegetation. EF11 was also assigned to forests at higher altitudes (which usually do not include invasive species) in the middle zone; and to rocky shores, areas of bare soil on escarpments and cliffs and in coastal areas, where, for example, migratory species nest.

The maintenance of natural evolutionary processes (EF12) was only assigned to natural and native ecosystems: lagoons and other waterbodies, areas with alpine and boreal heath, peat bogs and areas of natural vegetation.

The function of landscape attractiveness (EF13) was assigned to the entire island without discrimination among the ecosystems because of the exceptional scenic quality of the landscape on Pico Island and because the attractiveness of the landscape depends on the observer.

Pico Island is known for its vineyards (some classified as a UNESCO world heritage site) composed of many small rectangular and contiguous plots ('currais' in Portuguese) divided by walls of volcanic rock. Most of these areas are near villages in coastal areas, where other cultural elements may be found, such as small wineries. The function of cultural heritage (EF14) was therefore assigned to vineyards and urban areas in the coastal zone (escarpments and cliffs, coastal areas and transitional zones and lowlands).

The map showing the total number of functions is presented in Figure 4(a) and maps of the numbers of natural regulation, support and cultural functions are presented in Figure 4(b, c, d), respectively. Maps of each EF (Figure C1) are presented in Appendix C.

EFs were assigned to the entire area of Pico Island (Table 4). Areas with 12 overlapping functions (24.30% of the total area) were mainly in transitional zones and lowlands covered by forests, and 10 overlapping functions (22.33%) were mainly in the middle zone of Pico Island covered by semi-natural grasslands. Areas with 13 functions (8.47%) were mainly in coastal areas and transitional zones and lowlands covered by natural vegetation (mostly *M. faya*) and in the middle zone, also covered by natural vegetation (mostly endemic macaronesian heath). Areas with 14 functions (1.54%) were mainly in coastal areas covered by natural vegetation. Fewer overlapping functions occurred mainly in urban areas, agricultural land, rocky shores and areas of bare soil.

Table 4. Areas of the number (No.) of functions on Pico Island.

All functions		Natural regulation functions		Support functions		Cultural functions	
No.	Area (ha)	No.	Area (ha)	No.	Area (ha)	No.	Area (ha)
2	50.85 (0.11%)	0	2.63 (0.01%)	0	2414.31 (5.43%)	1	42,099.28 (94.65%)
3	2791.64 (6.28%)	1	3192.64 (7.18%)	1	14,554.07 (32.72%)	2	2380.55 (5.35%)
4	1632.44 (3.67%)	2	1361.30 (3.06%)	2	21,784.26 (48.98%)		**Total: 44,479.82**
5	2609.43 (5.87%)	3	1322.80 (2.97%)	3	5727.19 (12.88%)		
6	170.35 (0.38%)	4	1359.35 (3.06%)		**Total: 44,479.82**		
7	128.79 (0.29%)	5	4264.57 (9.59%)				
8	4100.75 (9.22%)	6	4325.02 (9.72%)				
9	4336.40 (9.75%)	7	9519.56 (21.40%)				
10	9933.53 (22.33%)	8	3122.98 (7.02%)				
11	3466.30 (7.79%)	9	8944.99 (20.11%)				
12	10,806.80 (24.30%)	10	7063.98 (15.88%)				
13	3768.61 (8.47%)		**Total: 44,479.82**				
14	683.94 (1.54%)						
	Total: 44,479.82						

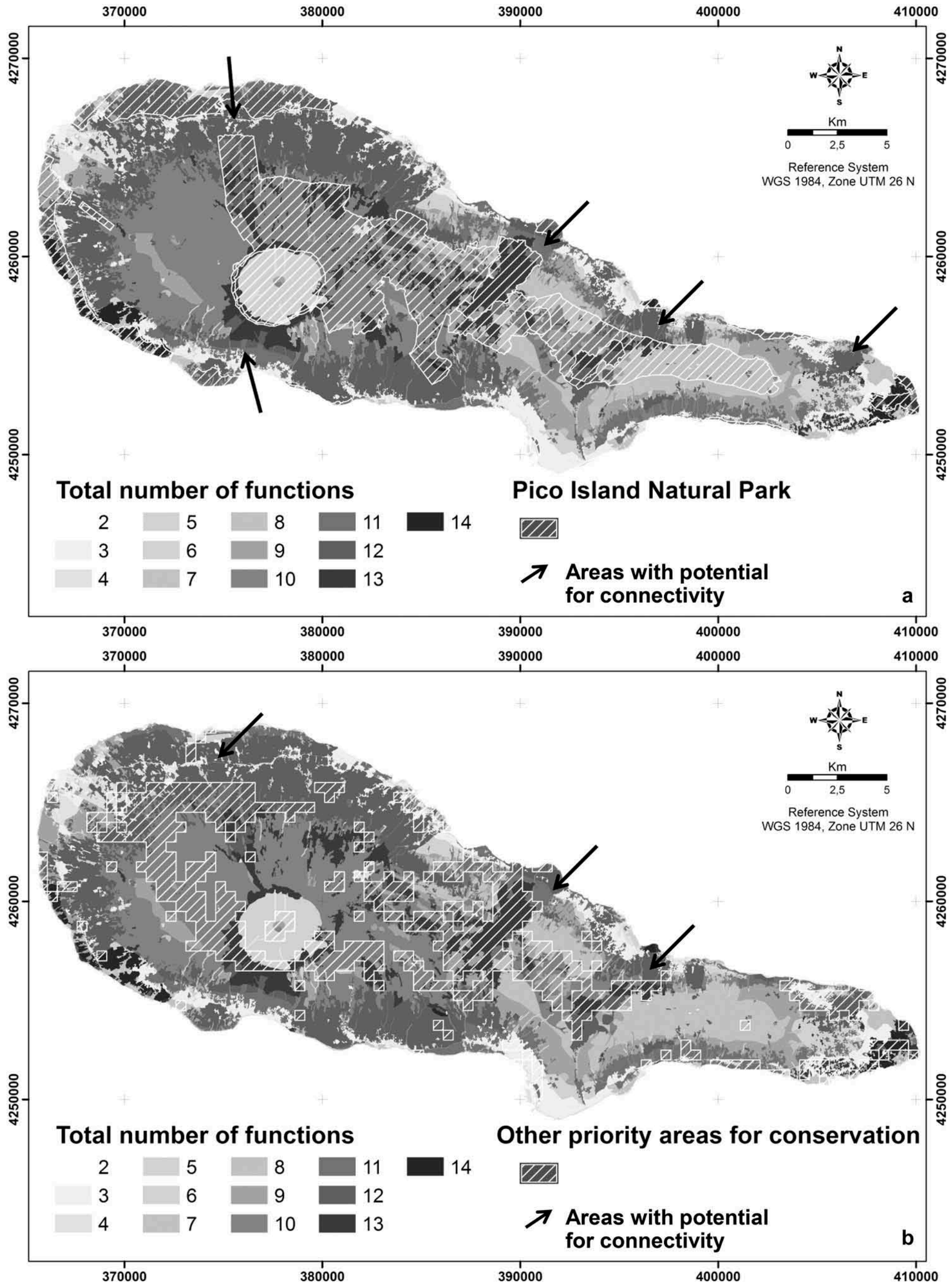

Figure 5. Total number of functions on Pico Island overlapping with Island Natural Park (a) and other priority areas for conservation (b); arrows indicate areas with potential for connectivity.

Table 5. Total number (No.) of EFs overlapping and not overlapping Pico's INP and other priority areas for conservation.

Total number of function		Overlapping INP		Overlapping other priority areas for conservation	
		Overlapping	Not overlapping	Overlapping	Not overlapping
No.	Area (ha)	Area (ha)	Area (ha)	Area (ha)	Area (ha)
2	50.85	11.54 (22.69%)	39.31 (77.31%)	12.85 (25.28%)	38.00 (74.72%)
3	2791.64	162.23 (5.81%)	2629.41 (94.19%)	474.15 (16.98%)	2317.48 (83.02%)
4	1632.44	502.70 (30.79%)	1129.74 (69.21%)	297.10 (18.20%)	1335.34 (81.80%)
5	2609.43	1303.85 (49.97%)	1305.58 (50.03%)	449.33 (17.22%)	2160.09 (82.78%)
6	170.35	11.22 (6.59%)	159.12 (93.41%)	45.48 (26.70%)	124.87 (73.30%)
7	128.79	120.99 (93.94%)	7.81 (6.06%)	12.28 (9.54%)	116.51 (90.46%)
8	4100.75	1956.31 (47.71%)	2144.43 (52.29%)	583.24 (14.22%)	3517.51 (85.78%)
9	4336.40	1332.48 (30.73%)	3003.93 (69.27%)	928.62 (21.41%)	3407.78 (78.59%)
10	9933.53	4017.17 (40.44%)	5916.36 (59.56%)	3352.07 (33.74%)	6581.46 (66.26%)
11	3466.30	787.20 (22.71%)	2679.10 (77.29%)	805.76 (23.25%)	2660.54 (76.75%)
12	10,806.80	2450.19 (22.67%)	8356.61 (77.33%)	2204.74 (20.40%)	8602.07 (79.60%)
13	3768.61	2649.02 (70.29%)	1119.59 (29.71%)	1980.72 (52.56%)	1787.89 (47.44%)
14	683.94	382.23 (55.89%)	301.71 (44.11%)	161.85 (23.66%)	522.09 (76.34%)
Total: 44,479.82		**15,687.14 (35.27%)**	**28,792.69 (64.73%)**	**11,308.20 (25.42%)**	**33,171.63 (74.58%)**

Some small patches (0.01%) corresponding to urban areas on escarpments and cliffs and areas of bare soil in marshes were not assigned natural regulation functions. The largest areas with natural regulation functions have 10, 9 or 7 functions occurring simultaneously (15.88%, 20.11% and 21.40%, respectively). Areas with 10 functions were mainly in coastal areas and transitional zones and lowlands covered by forests and natural vegetation; 9 functions were mainly in the middle zone covered by forests and natural vegetation; and 7 functions were also mainly in the middle zone of the island but covered mostly by grasslands. Areas with no support functions (5.43%) corresponded mostly to urban areas in coastal areas and in transitional zones and lowlands. A few more intensively managed grassland areas were also not assigned support functions. Most of the island (81.70%) was assigned one or two support functions (32.72% and 48.98%, respectively). Areas with one support function were mainly in coastal zones and in transitional zones and lowlands, and areas with two functions were mainly in the middle zone and marshes. Areas with all support functions (12.88%) were mainly covered by natural vegetation, both *M. faya* and endemic macaronesian heath. Cultural functions were present on the entire island, with two cultural functions (5.35%) mainly in coastal zones and in transitional zones and lowlands containing urban areas.

4.2. EFs, the INP and other areas for conservation

Most areas with the higher number of functions occurring simultaneously (14 and 13 functions with 55.89% and 70.29%, respectively) were in the INP (Figure 5(a) and Table 5), mainly coincident with nature reserves and protected landscapes for vineyard culture (see Figure A1 Appendix A for the locations of the classified PAs). Nature reserves on Mount Pico, however, were assigned only five functions. Areas with 12 and 11 functions were mainly outside the INP (22.67% and 22.71%, respectively) and were covered mostly by forests. Additionally, areas with seven functions were mostly in the INP (93.94%) corresponding to marshes. Areas with fewer functions (two, three or four functions overlapping simultaneously) were mainly outside the INP (77.31%, 94.19% and 69.21%, respectively), containing mostly urban areas and forests in coastal zones and in transitional zones and lowlands.

Areas with higher number of functions occurring simultaneously were both inside and outside the priority areas for the conservation of species (Figure 5(b)). Areas with 13 functions were mainly inside priority areas (52.56%), and areas with 14, 12 and 11 functions were mainly outside priority areas (76.34%, 79.60% and 76.75%, respectively) (Table 5).

5. Discussion

The main goal of this study was to contribute to implement the methodology proposed by Vergílio and Calado (2016), that is, identifying and mapping EFs to be integrated in the design of the ESt, in an expeditious way and easy to use for decision-makers, for territories lacking detailed data on biodiversity and individual studies on ecosystem functions and services.

In this case study of Pico Island, the areas of natural vegetation, peat bogs, and forests had higher total numbers of EFs. From the point of view of conservation, this result highlights the importance of natural areas with native species on Pico Island. More functions can provide more and better ecosystem services. Thus, caution is needed when licensing human activities to explore these areas. As mentioned previously, Vergílio and Calado (2016) suggested that ESt should cover the entire island, integrating a 'priority ESt' (that aggregates legally constrained areas) and a 'secondary ESt' (with less sensitive areas). Assuming that the priority ESt ensures enough constraints to activities to preserve the ecosystems, the secondary ESt must be able to combine human activities with the capacity of the ecosystems to accommodate such activities. For example, the assignment of EFs to production forests (with *Cryptomeria* or *Eucalyptus*) or invasive forests (with mainly *Pittosporum* and *Acacia*) is similar; however, their behavior is completely different from the point of view of territorial management. Production forests, despite having less biodiversity, may be used by several species as refugia or nurseries without significantly threatening other natural habitats. Invasive forest species, in contrast, have a high capacity to invade other areas in the Azores, especially abandoned lands, even if they are used by other species (e.g., as refugia or nurseries). The decreasing human population on Pico Island and concomitant abandonment of managed lands may contribute to amplify this process. Activities in invasive forests should thus be promoted, but only when the invasion can be reverted or at least controlled.

Pico's INP integrates classified areas with different management goals. Areas mainly aimed at preserving biodiversity also have more overlapping functions (Figure 5(a)). Further analysis focusing on each type of PA and the corresponding types of EFs would determine if the defined PA goals are in accordance with the EFs. Several areas containing a high number of EFs are outside the other priority areas for conservation. These priority areas were identified based on important species (Vergílio, Fonseca, et al. 2016) and the selection of EFs also considered other aspects of the environment. Despite this discrepancy, one may point out the potential of using EFs to identify and/or corroborate areas with possible connectivity between PAs and other priority areas for conservation (black arrows in Figure 5). These areas of connectivity are important because careful management may be applied without adding new legal restrictions to human activities but adapting human actions to minimize impact to the ecosystem processes.

This exploratory methodology presented both limitations and advantages. One of the major benefits is the possibility to integrate several EFs in a relatively simple way to be implemented by decision-makers with available expert knowledge, despite the absence of particular studies about each EF. The methodology is applicable to islands that have been scientifically studied or where experts are available for collaboration. The presence of a university system in the Azores with broad scientific expertise allows for the validation of assumptions, the listing of EFs and the assignment to each TU. Another advantage of the methodology is its dynamics, which enables its adaptation to other territories and modification over time, because it enables improvements by experts (it integrates sectoral information that may be included as more information becomes available).

The selection of functions in the proposed methodology was adapted to the study area, and the definition of TUs was a critical step. A too general definition of TUs would simplify the assignment of functions and produce a general map less able to support decision-making. TUs based on many biophysical features could increase the number of TUs and complicate function assignment. Finding a balance for selecting biophysical features used to define TUs is fundamental and will mainly depend on the objectives of the study. In this particular case study, it could have been useful to have more biophysical or more detailed features. For example, having more categories of land cover, such as production forests separated from invasive forests, could help distinguishing areas whose EFs might be more threatened or not.

Assuming that well-functioning ecosystems are able to provide services to communities, the methodology allows the identification of areas with more functions that will potentially contribute the most to provide those services. However, the presence of only one or two critical functions, either for the functioning of the ecosystem itself or for providing particular services to societies, may be as important as the presence of several other functions. Hansen and Pauleit (2014) explored how multifunctionality can be operationalized by approaches developed and tested in ecosystem services research, specifically as a contribution to assess the integrity of green infrastructure networks for urban areas. These authors posit that potential conflicts between ecosystem services might be overlooked if multifunctionality is understood only 'as a quantitative sense of the more functions the better.' They also advert for the potential increase of environmental injustice for particular groups of society, if the capacity of ecosystems to provide services and social questions of demand and access to those benefits are assessed and planned independently. These authors suggest the integration of a broad range of ecological and social aspects to meet the holistic goals of green infrastructure planning. One advantage of the approach proposed in the present study is the integration of both perspectives of nature conservation (by integrating functions for the internal balance of ecosystems) and community development (by integrating functions with interest for societies). Processes integrating these two perspectives might, however, produce multiple and conflicting interests, hindering the decision on what kind of human actions to allow in a certain area with high value for both species conservation and the development of human activities.

Aretano et al. (2013), for example, refer that the success of a management plan 'essentially depends on its ability to enhance the involvement of several stakeholders (decision-makers, residents, NGO) with the aim to preserve the area.' Inkoom et al. (2017) developed a framework for integrating ecosystem services into land-use planning and suggested the adoption of a transdisciplinary planning approach, integrating strategic environmental assessment, participatory planning, geographic information systems and human resource capacity training of all relevant actors and stakeholders. To increase the potential of the methodology proposed here and to overcome problems arising from different combinations of EFs, a multi-criteria decision-making (MCDM) model is proposed to be used in the theoretical framework for the ESt. MCDM is a technique for solving problems involving multiple criteria when there is more than one optimal solution (Majumder 2015). In these situations, using the preferences of the decision-makers and stakeholders who have different perceptions and values (Oikonomou et al. 2011), it is necessary to distinguish and select among several solutions. Oikonomou et al. (2011) also suggested that MCDM can be an alternative to the economic valuation of ecosystem services or functions, which may not adequately assess the complex nature of EFs and services and the multiple conflicting objectives and values involved, and proposed a conceptual framework that combines EF analysis, multi-criteria evaluation and social-research methodologies for introducing an EF-based planning and management approach. MCDM will thereby be the final step to define and map the secondary ESt, as suggested by Vergílio and Calado (2016). This technique will allow stakeholders to answer questions such as: is the number of functions more important than the type of functions; how many functions are fundamental to preserve; if all areas are important, which ones are the most important?

Some aspects, however, have to be considered when adopting an MCDM in the Azores for designing the ESt. Independent of the technique adopted, there might be the need to inform stakeholders about the theoretical concepts and objectives. Considering that several environmental aspects will be discussed and the complexity of ecosystems and effects of human actions, this will allow everyone involved to be able to 'speak the same language' and give reasoned opinions. Considering the diversity of stakeholders that might be involved and their different backgrounds, the information should be as simple and clear as possible in order to avoid misunderstandings. A successful stakeholder engagement process contributing to design the ESt might be crucial to successfully implement it, as suggested by Kopperoinen et al. (2014):

> By involving both experts and local and regional actors in assessing ES [ecosystem services] provision potential we can add local knowledge to the general scientific understanding. (...) The group discussions involved in our method provided an additional benefit, as the experts and local and regional actors felt that this discussion platform enhanced their understanding of both GI [green infrastructure] and ES [ecosystem services].

This paper is a first contribution for the Azores to include EFs into ESt design in a practical way and applicable in the short term. Future research, however, should be developed, including investing in the assessment and mapping of individual EFs. A comprehensive knowledge of territories will greatly improve integrated management decisions and measures. Future developments for the proposed methodology could include a more extensive expert consultation as a pilot test for ranking EFs to overcome the bias from using the number of EFs. Also, the implementation of an MCDM process will contribute to validate this methodology, gathering stakeholders' perspective about its practicality. Finally, it would be interesting to explore this approach to include EFs not only in the design of the ESt, but in the overall design of the Portuguese spatial planning defined in MMPs, including other categories of EFs, such as production functions, and increasing the contribution of social issues.

6. Conclusion

This study presented an exploratory strategy for identifying and mapping EFs on small islands. The method contributes to the definition of ESt, one of the elements integrating Portuguese MMPs. These plans are being reviewed on Pico Island, so a simple straightforward methodology for ESt visualization is needed. The analysis suggests that the EFs are a useful tool that can be integrated in the procedures of spatial planning, because it provides an easy way to spatially visualize EFs, bringing a new perspective of the landscape and its potential. It also suggests that the proposed methodology may help to define ESt because it gives an integrated overview of ecosystems and their multiple functions, thereby contributing to the identification of the systems for protecting the values of natural, cultural, agricultural and forest resources, as required by Azorean legislation (Regional Legislative Decree No. 35/2012/A of 2012). MMPs are spatial plans defined at the local scale and must comply with regional legislation. The primary ESt (Vergílio and Calado 2016) aggregates areas with legal protection and complies with regional legislation. The proposed methodology integrating EFs identifies the areas with more functions and higher potential to provide ecosystem services. The use of an MCDM technique may enable the integration of community needs and expectations, resulting in a more comprehensive process for future developments.

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Ecosystem functions at the island scale: a contribution to the design of ecological structure

Marta Vergílio, Peter V. August; Helena Calado, Catarina Fonseca

Appendix A. Pico's Island Natural Park

The Azorean terrestrial PA network is organized in nine Island Natural Parks (INPs), one per island (Calado et al. 2009; Regional Legislative Decree No. 15/2012/A), composed of PAs of different categories (based on the categories of the International Union for Conservation of Nature). The category assigned to each area depends on its management goals and generally represents a gradation of naturalness (Dudley 2008). The categories of PAs on Pico Island range from 'nature reserves' to 'protected areas for resource management'.

Pico has the largest classified area in the Azores (approximately 35% of the island territory), and its INP is composed of 22 areas (Figure A.1) (19 terrestrial PAs and three marine PAs): four nature reserves, one natural monument, eight PAs for habitat/species management, six protected landscapes and three PAs for resource management (all three are coastal and marine areas).

Appendix B. Territorial units

The combination of the morphoclimatic features, soil subclasses and land covers on Pico Island produced 86 territorial units (TUs) (Figure B.1). TUs with larger areas (Table B.1) are grasslands in the middle zone (TU code 30 with 11054 ha), forests in transitional zones and lowlands (TU code 20 with 7643 ha), forests in the middle zone (TU code 28 with 4328 ha) and grasslands in the middle zone (TU code 38 with 3942 ha). TUs with smaller areas are rocky shores in the middle zone (TU code 32 with 0.003 ha), water-bodies in marshes (TU code 73 with 0.05 ha) and grasslands and areas of bare soil on escarpments and cliffs (TU codes 4 and 5 with 0.097 and 0.083 ha, respectively).

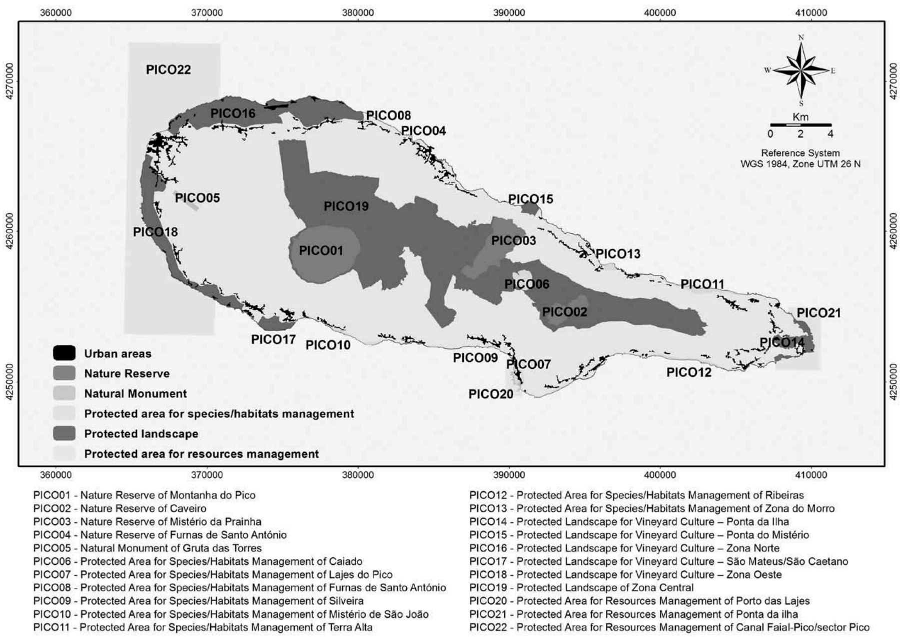

Figure A.1. Pico Island Natural Park.

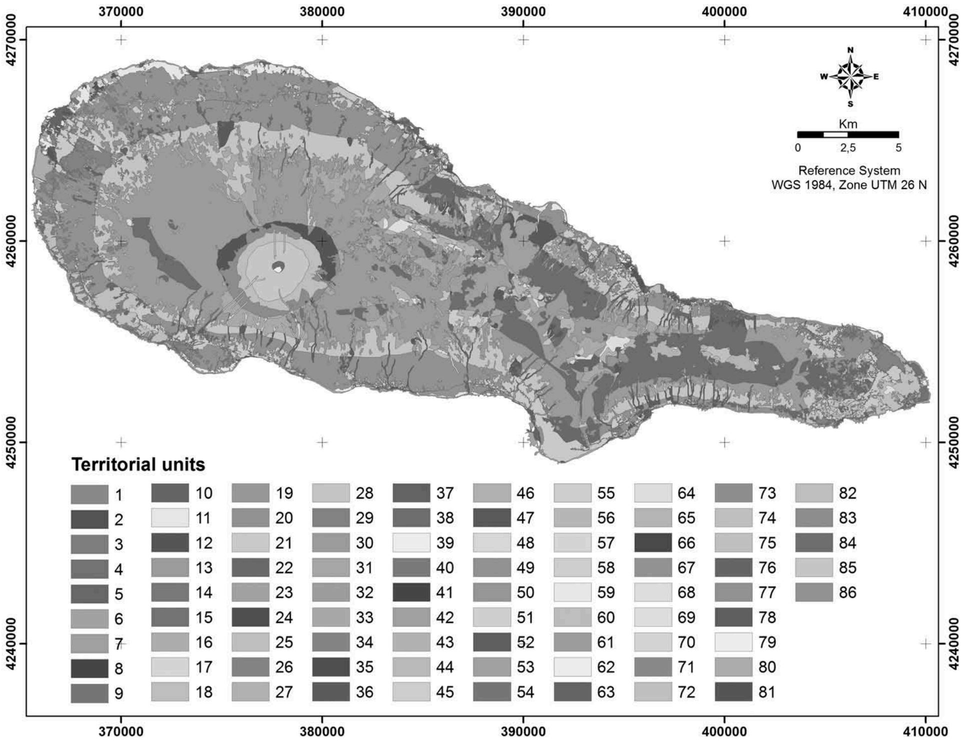

Figure B.1. Territorial units defined for Pico Island based on morphoclimatic features, soil subclasses and land covers.

Table B.1. Territorial units for Pico Island based on morphoclimatic features, soil subclasses and land covers; corresponding number of polygons; minimum, maximum and total areas and percentage of the island territory (-, without limitations; e, soils with high susceptibility to erosion; s, soil limitations in the rooting zone; w, soil with excess water (drenching); TU, territorial unit). Territorial units with larger areas are highlighted in dark grey, and territorial units with smaller areas are highlighted in light grey.

Morphoclimatic Features	Soil subclass	Land cover	TU code	Number of polygons	Minimum area (ha)	Maximum area (ha)	Total area (ha)	% Island
Escarpments and cliffs	-	Urban	1	11	0.006	0.241	0.829	0.0019
		Forests	2	10	0.001	0.157	0.604	0.0014
		Agriculture	3	6	0.000	0.132	0.386	0.0009
		Grasslands	4	2	0.031	0.066	0.097	0.0002
		Bare soil	5	3	0.004	0.072	0.083	0.0002
		Rocky shore	6	20	0.559	63.475	517.840	1.1642
		Natural vegetation	7	4	0.008	0.157	0.240	0.0005
		Vineyards	8	7	0.001	0.288	0.672	0.0015
	e	Rocky shore	9	2	3.489	4.385	7.874	0.0177
Coastal areas	-	Urban	10	58	0.001	98.014	298.517	0.6711
		Forests	11	70	0.051	250.334	617.204	1.3876
		Agriculture	12	73	0.061	34.706	228.372	0.5134
		Grasslands	13	4	0.058	3.777	6.220	0.0140
		Bare soil	14	25	0.193	7.906	47.791	0.1074
		Natural vegetation	15	26	0.017	57.868	136.337	0.3065
		Vineyards	16	154	0.000	113.554	475.606	1.0693
	e	Forests	17	1	0.314	0.314	0.314	0.0007
		Bare soil	18	2	0.177	0.592	0.769	0.0017
Transitional zones and lowlands	-	Urban	19	60	0.013	249.533	549.179	1.2347
		Forests	20	169	0.001	1550.535	7643.306	17.1838
		Agriculture	21	214	0.001	294.662	2526.170	5.6794
		Grasslands	22	93	0.000	309.566	1130.139	2.5408
		Bare soil	23	70	0.007	26.430	167.264	0.3760
		Rocky shore	24	11	0.000	0.131	0.344	0.0008
		Natural vegetation	25	44	0.312	231.232	864.355	1.9433
		Vineyards	26	264	0.000	240.862	1035.863	2.3288
Middle zone	-	Urban	27	3	1.576	2.049	5.418	0.0122
		Forests	28	106	0.013	1154.703	4328.464	9.7313
		Agriculture	29	27	0.018	20.848	128.556	0.2890
		Grasslands	30	99	0.000	4065.394	11054.264	24.8523
		Bare soil	31	23	0.008	41.220	78.213	0.1758
		Rocky shore	32	1	0.003	0.003	0.003	0.0000
		Natural vegetation	33	161	0.000	295.922	2407.989	5.4137
		Vineyards	34	1	0.297	0.297	0.297	0.0007
	e	Urban	35	1	0.107	0.107	0.107	0.0002
		Forests	36	53	0.002	188.696	501.322	1.1271
		Agriculture	37	2	0.113	3.603	3.716	0.0084
		Grasslands	38	51	0.000	1721.366	3942.253	8.8630
		Waterbodies	39	13	0.022	0.091	0.647	0.0015
		Bare soil	40	5	0.134	2.385	4.582	0.0103
		Peat bogs	41	2	0.419	1.217	1.636	0.0037
		Natural vegetation	42	59	0.025	423.872	1163.372	2.6155
	e. s	Natural vegetation	43	1	6.831	6.831	6.831	0.0154
	s	Forests	44	2	8.398	18.945	27.343	0.0615
		Grasslands	45	8	0.000	46.843	108.053	0.2429
		Natural vegetation	46	7	0.561	48.736	88.456	0.1989
Lagoons	w	Waterbodies	47	1	0.152	0.152	0.152	0.0003
	e	Waterbodies	48	25	0.108	5.714	22.290	0.0501
Peat bogs	e	Grasslands	49	2	0.267	25.085	25.352	0.0570
		Peat bogs	50	2	0.267	22.986	23.253	0.0523
Valleys	-	Urban	51	31	0.015	1.517	9.199	0.0207
		Forests	52	82	0.023	25.203	489.225	1.0999
		Agriculture	53	63	0.001	4.963	75.059	0.1687
		Grasslands	54	78	0.002	15.523	245.496	0.5519
		Bare soil	55	5	0.208	8.257	11.469	0.0258
		Rocky shore	56	7	0.001	0.093	0.359	0.0008
		Natural vegetation	57	48	0.027	15.917	136.489	0.3069
		Vineyards	58	10	0.000	2.559	5.426	0.0122
	e	Forests	59	2	4.941	5.207	10.148	0.0228
		Bare soil	60	3	4.639	10.677	21.836	0.0491
		Natural vegetation	61	5	0.010	3.973	5.672	0.0128

(*Continued*)

Table B.1. (Continued).

Morphoclimatic Features	Soil subclass	Land cover	TU code	Number of polygons	Minimum area (ha)	Maximum area (ha)	Total area (ha)	% Island
Marshes	-	Urban	62	2	0.696	0.801	1.497	0.0034
		Forests	63	14	0.048	13.929	60.885	0.1369
		Agriculture	64	4	0.209	3.860	8.329	0.0187
		Grasslands	65	19	0.122	135.246	582.179	1.3089
		Waterbodies	66	3	0.004	0.099	0.185	0.0004
		Bare soil	67	8	0.008	3.861	7.933	0.0178
		Peat bogs	68	12	0.017	1.441	5.797	0.0130
		Natural vegetation	69	22	0.434	66.711	255.087	0.5735
		Vineyards	70	3	0.980	7.149	14.159	0.0318
	e	Forests	71	1	0.106	0.106	0.106	0.0002
		Grasslands	72	12	0.135	59.402	134.677	0.3028
		Waterbodies	73	1	0.050	0.050	0.050	0.0001
		Bare soil	74	1	0.107	0.107	0.107	0.0002
		Peat bogs	75	5	0.003	0.331	1.093	0.0025
		Natural vegetation	76	12	0.027	66.705	86.498	0.1945
	s	Grasslands	77	2	3.090	8.990	12.079	0.0272
		Natural vegetation	78	1	9.371	9.371	9.371	0.0211
Mount Pico	-	Alpine and boreal heath	79	1	8.089	8.089	8.089	0.0182
		Bare soil	80	1	0.266	0.266	0.266	0.0006
	e	Grasslands	81	2	138.630	284.455	423.084	0.9512
		Bare soil	82	1	525.105	525.105	525.105	1.1805
		Natural vegetation	83	2	23.428	460.979	484.407	1.0890
	e. s	Alpine and boreal heath	84	1	18.896	18.896	18.896	0.0425
		Bare soil	85	1	640.784	640.784	640.784	1.4406
	s	Grasslands	86	1	9.836	9.836	9.836	0.0221
						TOTAL (ha)	**44479.824**	**100.0000**

Appendix C. Individual ecosystem functions

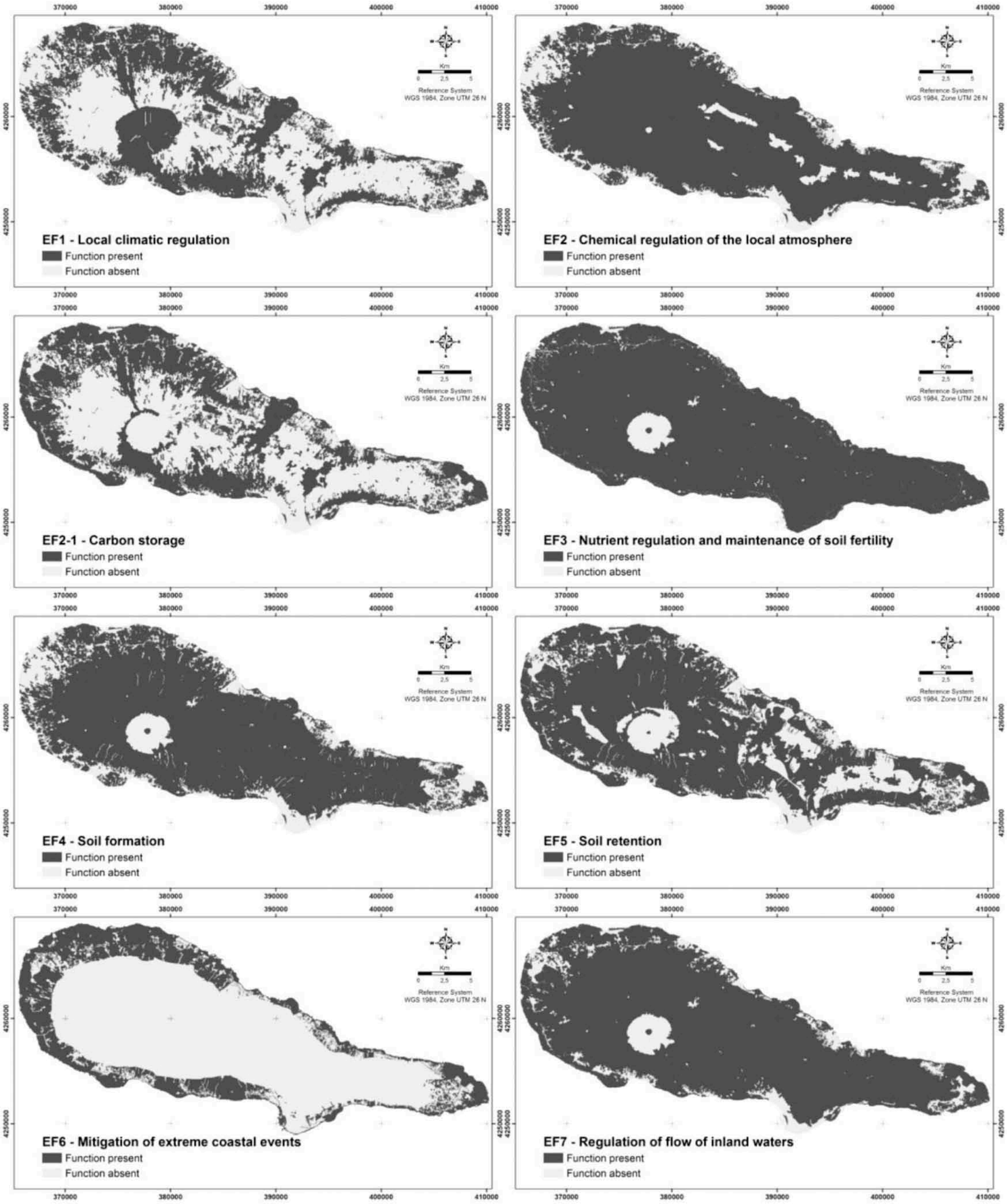

Figure C.1. Maps of individual ecosystem functions.

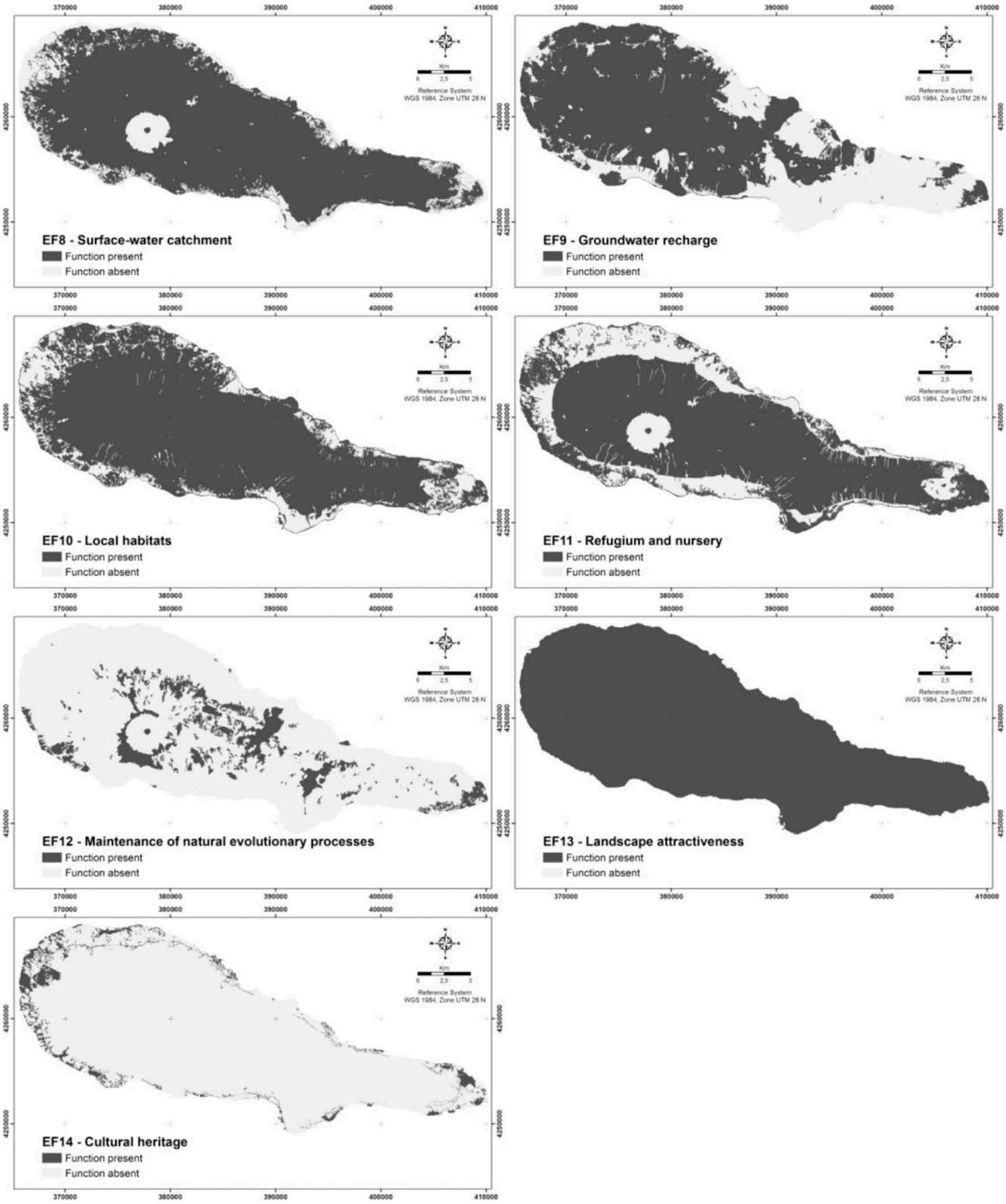

Figure C.1. continued.

References

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Regional Legislative Decree No. 15/2012/A of April 2, Establishes the Legal Regime of Nature Conservation and Biodiversity Protection (in Portuguese).