HAROKOPIO UNIVERSITY

School of Environment, Geography and Applied Economics

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MAPPING AND VALUATION OF ECOSYSTEM SERVICES FOR INFORMED DECISION MAKING IN SPATIAL PLANNING

DOCTORAL THESIS

by

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ABSTRACT

Everyone in the world depends on Earth's ecosystems and the services they provide, such as food, water, disease management, climate regulation, spiritual fulfillment, and aesthetic enjoyment. Ecosystem Services (ESs) are defined as the direct or indirect contribution of ecological structure and processes to human well-being in the form of (1) provisioning, (2) regulating & maintenance and (3) cultural services (based on the Common International Classification of Ecosystem Services - CICES). This implies that mankind is strongly dependent on well-functioning ecosystems and natural capital that are the basis for a constant flow of ESs from nature to society. Mapping and assessing ESs represent important approaches towards understanding the link between the provision of ESs and human society, which, in turn, facilitates decision-making and management. To effectively manage multiple ESs, it is essential to understand how the dynamics of ESs maintain healthy ecosystems to avoid potential negative impacts on human well-being in the context of sustainable development. In this regard, implementing the ES framework in practice requires the identification of the complex interactions among ESs, and between ESs and human demand to optimize future ES provision and to mitigate current trade-offs. However, human demands for natural resources continue to grow rapidly, risking the short supply of ES. By accounting for both the supply and demand ES, it is possible to identify where ESs are not able to satisfy human needs.

Mediterranean islands are widely recognized as biodiversity hotspots, with a long history of human activities shaping multi-functional landscapes. Socio-economic and environmental factors are among the most important factors driving the creation of diverse landscapes, with a high supply of ESs. However, these factors, along with climate change, could also have irreversible consequences on local ecosystems, which might have negatively impacted ESs. Within this context, this thesis aimed to improve the understanding of ES occurrence and ES relationships in complex and diverse Mediterranean ecosystems, such as those found in the Ionian Islands. This improved understanding offers important information to decision-makers and landscape planners about the possible impacts that management decisions and actions could cause on sensitive ecosystems. Specifically, the main objectives were to (1) assess the spatial dynamics and interactions among the supply of multiple ES, (2) identify the spatial congruence between the supply and demand of ES, and (3) reveal the socio-ecological factors that determine the spatial distribution of ES bundles in the four prefectures of Ionian Islands; namely, Corfu, Lefkada, Kefalonia, and Zakynthos.

First, using a combined set of biophysical indicators and models, ESs were mapped to reveal their spatial distribution. Additionally, ES interactions were investigated by analyzing ES relationships, identifying ES bundles (sets of ESs that repeatedly occur together across space and time), and specifying ES occurrence within these bundles. The three ES groups (provisioning, regulating and cultural) exhibited similar patterns on some islands, but differed on other islands were areas of high recreation presented low provisioning and regulating ESs. Temporal variations showed both stability and changes to the supply and relationships of ESs. Among the islands, different patterns were caused by the degree of mixing between natural vegetation and olive orchards, as the olive bundle delivered the most ESs, while the non-vegetated bundle delivered negligible amounts of ESs. The findings of the spatial and temporal variation in ESs appear to be determined by agriculture, land abandonment, and increasing tourism, as well as the occurrence of fires.

Second, using both biophysical and economic indicators, the capacity of ecosystems to provide benefits and societal needs were assessed to reveal ES spatial similarities and mismatches. The results showed that cropland and urban areas presented high demand for all three ES, due to the high presence of the human population, along with tourism activities. In comparison, more than 50% of the Ionian Islands are characterized by natural forests and olive orchards, leading large areas to be dominated by excess ES supply or by similar amounts of both ES supply and demand. The hot spot analysis (Getis-Ord Gi* statistic) conducted to identify spatial mismatches delineated zones with high connectivity, which could facilitate the prioritization of conservation areas. For areas where an unsustainable regime was revealed, recommendations on how to maintain or shift current spatial policies were given to improve the decision-making process. For the most part, results signified that human demands for ES were fulfilled. Consequently, understanding the balance between ES supply and demand can facilitate sustainable spatial planning and enhance the quality of life.

Third, to support informed decision-making on landscape management, and implement appropriate planning actions, the final objective of this thesis was to reveal the importance of socio-ecological factors in shaping ES bundles. In specific, 17 socio-ecological variables were explored using an ensemble machine learning method (Random Forest) for their contribution to explaining the supply and demand of ESs. The results showed that the most important variables for the distribution of ES supply bundles were landscape heterogeneity, elevation, slope, landscape connectivity, and population. In comparison, variables representing elevation, slope, and population were among the most important variables contributing to ES demand bundles.

The findings demonstrated that research on ESs should account for underlying socio-ecological drivers that influence the supply and demand of ES to improve our understanding of the possible impacts of future management decisions regarding the diverse Mediterranean landscapes of the Ionian Islands.

In conclusion, ecosystem services are regarded as an effective communication tool to bridge the knowledge of science, policy-making, and practice, eventually becoming a major tool for decision making on global, national, regional and local scales.

Keywords: Ecosystem services, spatial analysis, mapping, assessing, supply, demand, socio-ecological determinants, decision-making, Ionian Islands

ΠΕΡΙΛΗΨΗ [Abstract in Greek]

Ο άνθρωπος εξαρτάται εξ ολοκλήρου από τα οικοσυστήματα της Γης και τις υπηρεσίες που παρέχουν, όπως η διάθεση τροφής και νερού, η διαχείριση ασθενειών, η ρύθμιση του κλίματος, η πνευματική ευημερία και η αισθητική απόλαυση. Οι οικοσυστημικές υπηρεσίες (ΟΥ) ορίζονται ως η άμεση ή έμμεση συμβολή της οικολογικής δομής και των διαδικασιών στην ανθρώπινη ευημερία με τη μορφή (1) προμηθευτικών υπηρεσιών, (2) ρυθμιστικών υπηρεσιών και υπηρεσιών διατήρησης, και (3) πολιτιστικών υπηρεσιών (σύμφωνα με την Κοινή Παγκόσμια Ταξινόμηση των Οικοσυστημικών Υπηρεσιών - *CICES*). Αυτό σημαίνει ότι η ανθρωπότητα εξαρτάται σε μεγάλο βαθμό από το φυσικό κεφάλαιο και από υψηλής λειτουργικότητας οικοσυστήματα, τα οποία αποτελούν τη βάση μιας σταθερής ροής ΟΥ. Η χαρτογράφηση και η αξιολόγηση των ΟΥ παρέχουν σημαντικές πληροφορίες για την κατανόηση της σχέσης μεταξύ της παροχής ΟΥ και της κοινωνίας, οι οποίες, με τη σειρά τους, διευκολύνουν τη λήψη αποφάσεων και την περιβαλλοντική διαχείριση. Έτσι, για την αποτελεσματική διαχείριση πολλαπλών ΟΥ, είναι σημαντικό να κατανοήσουμε πως η δυναμική των ΟΥ διατηρεί υγιή οικοσυστήματα ώστε να αποφευχθούν πιθανές αρνητικές επιπτώσεις στην ανθρώπινη ευημερία στο πλαίσιο της βιώσιμης ανάπτυξης. Από την άποψη αυτή, η εφαρμογή των ΟΥ στην πράξη απαιτεί τον εντοπισμό των πολύπλοκων αλληλεπιδράσεων αναμεταξύ των ΟΥ και μεταξύ των ΟΥ και της ανθρώπινης ζήτησης για τη βελτιστοποίηση της μελλοντικής παροχής ΟΥ και τον μετριασμό των πιθανών ανταλλαγών (*trade-offs*). Ωστόσο, η ανθρώπινη ζήτηση για φυσικούς πόρους εξακολουθεί να αυξάνεται με ραγδαίο ρυθμό, με κίνδυνο τη μείωση παροχής σημαντικών ΟΥ. Έτσι, με την καταγραφή τόσο της προσφοράς όσο και της ζήτησης για ΟΥ, είναι δυνατό να εντοπιστούν οι ζώνες ή οι περιοχές στις οποίες οι ΟΥ είναι σε θέση να ικανοποιήσουν τις ανθρώπινες ανάγκες.

Τα νησιά της Μεσογείου είναι ευρέως αναγνωρισμένα ως θερμά σημεία (*hotspots*) βιοποικιλότητας, με μακροχρόνια επίδραση ανθρώπινων δραστηριοτήτων που διαμόρφωσαν πολύ-λειτουργικά τοπία. Οι κοινωνικό-οικονομικοί και περιβαλλοντικοί παράγοντες συγκαταλέγονται μεταξύ των σημαντικότερων παραγόντων που οδηγούν στη δημιουργία τέτοιων ποικίλων τοπίων, τα οποία παρέχουν πολλαπλές ΟΥ. Ωστόσο, αυτοί οι παράγοντες, συνοδευόμενοι και οδηγούμενοι από την κλιματική αλλαγή, μπορεί να έχουν μη αναστρέψιμες συνέπειες στα τοπικά οικοσυστήματα, και επομένως στις ΟΥ που παρέχονται. Στο πλαίσιο αυτό, η παρούσα διδακτορική διατριβή φιλοδοξεί να συμβάλει στην κατανόηση των ΟΥ και των σχέσεων μεταξύ τους, οι οποίες λαμβάνουν χώρα σε πολύπλοκα και ποικίλα μεσογειακά

οικοσυστήματα, όπως εκείνα που χαρακτηρίζουν τα Ιόνια νησιά. Αυτή η ολοκληρωμένη εικόνα μπορεί να προσφέρει σημαντικές πληροφορίες στους υπεύθυνους λήψης αποφάσεων και στους διαχειριστές του τοπίου σχετικά με τις πιθανές επιπτώσεις που μπορεί να προκαλέσουν διαχειριστικές αποφάσεις και δράσεις σε ευαίσθητα οικοσυστήματα. Συγκεκριμένα, οι κύριοι στόχοι ήταν (1) να εκτιμηθεί η χωρική και χρονική δυναμική πολλαπλών ΟΥ, καθώς και οι αλληλεπιδράσεις μεταξύ τους, (2) να προσδιοριστεί η χωρική συμφωνία/αντιστοιχία μεταξύ της προσφοράς και της ζήτησης για ΟΥ και (3) να εντοπιστεί ο βαθμός συνεισφοράς κοινωνικό-οικολογικών παραγόντων στη χωρική κατανομή των δεσμών ΟΥ στους τέσσερις νομούς των Ιονίων Νήσων · δηλαδή την Κέρκυρα, τη Λευκάδα, την Κεφαλονιά και τη Ζάκυνθο.

Αρχικά, χρησιμοποιώντας μια σειρά βιοφυσικών δεικτών και μοντέλων, χαρτογραφήθηκε στην περιοχή μελέτης η χωρική κατανομή των ΟΥ. Επιπλέον, διερευνήθηκαν οι αλληλεπιδράσεις αναμεταξύ των ΟΥ αναλύοντας τις σχέσεις τους, προσδιορίζοντας τις δέσμες ΟΥ (σύνολα ΟΥ που εμφανίζονται ταυτόχρονα χωρικά και χρονικά) και προσδιορίζοντας την σύσταση και ένταση των ΟΥ μέσα στις δέσμες αυτές. Οι τρεις βασικές ομάδες ΟΥ (προμηθευτικές, ρυθμιστικές και πολιτισμικές) εμφάνισαν παρόμοια πρότυπα σε ορισμένα νησιά, αλλά διέφεραν σε νησιά όπου περιοχές με υψηλή παροχή αναψυχής παρουσίασαν ταυτόχρονα χαμηλής έντασης προμηθευτικές και ρυθμιστικές υπηρεσίες. Οι χρονικές μεταβολές έδειξαν τόσο σταθερότητα όσο και αλλαγές στην παροχή και τις σχέσεις μεταξύ ΟΥ. Μεταξύ των νησιών, διαφορετικά πρότυπα προκλήθηκαν από το βαθμό μίξης φυσικής βλάστησης και ελαιώνων, καθώς η δέσμη ελαιώνων παρείχε πολλαπλές ΟΥ, ενώ η αστική-χωρίς βλάστηση δέσμη παρείχε μειωμένη ποσότητα ΟΥ. Τα ευρήματα της εργασίας σχετικά με τη χωρική και χρονική διακύμανση των ΟΥ φαίνεται να καθορίζονται από τη γεωργία, την εγκατάλειψη ή/και εντατικοποίηση της γης, την αύξηση του τουρισμού και την συχνότητα πυρκαγιών.

Έπειτα, διερευνήθηκαν οι χωρικές ομοιότητες και αναντιστοιχίες μεταξύ της ικανότητας των οικοσυστημάτων να παρέχουν υπηρεσίες και της ζήτησης της κοινωνίας για τις υπηρεσίες αυτές, χρησιμοποιώντας βιοφυσικούς και οικονομικούς δείκτες. Τα αποτελέσματα έδειξαν ότι οι αγροτικές και αστικές περιοχές παρουσίασαν μεγάλη ζήτηση, λόγω της υψηλής παρουσίας του ανθρώπινου πληθυσμού και των τουριστικών δραστηριοτήτων στις περιοχές αυτές. Αντίθετα, τα δάση και ελαιώνες, που αποτελούν πάνω από το 50% των νησιών του Ιονίου οδήγησαν μεγάλες εκτάσεις περιοχών να κυριαρχούνται από πλεονάζουσα παροχή ΟΥ ή ισορροπία μεταξύ παροχής και ζήτησης. Η ανάλυση χωρικών προτύπων που πραγματοποιήθηκε για τον εντοπισμό ομοιογενών χωρικών ζωνών με υψηλή αναντιστοιχία παροχής-ζήτησης διευκόλυνε τον εντοπισμό περιοχών προτεραιότητας για διατήρηση. Για περιοχές όπου φαίνεται να υπάρχει ένα μη βιώσιμο καθεστώς διαχείρισης, ήταν δυνατή η εύρεση εναλλακτικών λύσεων σχετικά με τη διατήρηση ή τη μετατόπιση των χωροταξικών πολιτικών για τη βελτίωση της διαδικασίας λήψης αποφάσεων. Γενικότερα, τα αποτελέσματα έδειξαν ότι σε μεγάλο βαθμό η ζήτηση της κοινωνίας για σημαντικές υπηρεσίες καλύπτεται από την παροχή υπηρεσιών των οικοσυστήματων. Κατά συνέπεια, η κατανόηση της ισορροπίας μεταξύ παροχής και ζήτησης μπορεί να διευκολύνει τον βιώσιμο χωροταξικό σχεδιασμό και τη βελτίωση της ποιότητας ζωής.

Τέλος, για να υποστηριχθεί η λήψη τεκμηριωμένων αποφάσεων σχετικά με τη διαχείριση του τοπίου και για την υλοποίηση κατάλληλων ενεργειών σχεδιασμού, ο τελικός στόχος αυτής της εργασίας ήταν να εντοπίσει το βαθμό συνεισφοράς των κοινωνικό-οικολογικών παραγόντων στη διαμόρφωση των δεσμών ΟΥ. Συγκεκριμένα, διερευνήθηκαν 17 κοινωνικό-οικολογικές μεταβλητές, με τη χρήση μεθόδου μηχανικής μάθησης (*Random Forest*), για τη συμβολή τους στην εξήγηση και διαμόρφωση της παροχής και ζήτησης ΟΥ. Τα αποτελέσματα έδειξαν ότι οι σημαντικότερες μεταβλητές για τη διαμόρφωση των δεσμών παροχής ΟΥ ήταν η ετερογένεια και η συνδεσιμότητα τοπίου, το υψόμετρο, οι κλίσεις, και ο πληθυσμός. Συγκριτικά, οι μεταβλητές που αντιπροσωπεύουν τοπογραφικά χαρακτηριστικά (υψόμετρο και κλίσεις) και ο πληθυσμός συγκαταλέγονται μεταξύ των σημαντικότερων μεταβλητών που συμβάλλουν στη ζήτηση από τη κοινωνία για συγκεκριμένες ΟΥ. Έτσι, μελλοντικές έρευνες για ΟΥ θα πρέπει να λαμβάνουν υπόψη τους κοινωνικό-οικολογικούς παράγοντες που επηρεάζουν την παροχή και τη ζήτηση των ΟΥ για την κατανόηση των πιθανών επιπτώσεων μελλοντικών διαχειριστικών αποφάσεων σχετικά με τα ποικίλα μεσογειακά τοπία, όπως αυτά των Ιονίων Νήσων.

Συμπερασματικά, οι οικοσυστημικές υπηρεσίες θεωρούνται ως ένα αποτελεσματικό εργαλείο γεφύρωσης μεταξύ ερευνητικών αποτελεσμάτων, και χάραξης πολιτικής, καθιστώντας τες τελικά ένα σημαντικό μέσο λήψης αποφάσεων σε παγκόσμια, εθνική, περιφερειακή και τοπική κλίμακα.

Λέξεις κλειδιά: Οικοσυστημικές υπηρεσίες, χωρική ανάλυση, χαρτογράφηση, αξιολόγηση, παροχή, ζήτηση, κοινωνικό-οικολογικοί επεξηγηματικοί παράγοντες, λήψη αποφάσεων, Ιόνια νησιά

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LIST OF ABBREVIATIONS AND ACRONYMS

AHP	Analytical Hierarchy Process
ANOVA	Analysis of Variance
AUC-ROC	Area Under the Curve-Receiver Operating Characteristics
CICES	Common International Classification of Ecosystem Services
CR	Climate Regulation
DM	Direct market valuation approaches
DPSIR	Drivers-Pressures-State-Impact-Response model of intervention
EP	Erosion Prevention
ES	Ecosystem Service (singular)
ESs	Ecosystem Services (plural)
ESD	Ecosystem Service Demand
ESDR	Ecological Supply-Demand Ratio
ESS	Ecosystem Service Supply
EVI	Enhanced Vegetation Index
FP	Food Provision
GHG	Greenhouse Gas (emissions)
HCA	Hierarchical Cluster Analysis
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
LP	Livestock Provision
MEA	Millennium Ecosystem Assessment
MAES	Mapping and Assessment of Ecosystems and their Services
MCA	Multivariate Correspondence Analysis
MT	Materials from Timber
NEI	Naturalness Evaluation Index
NS	Nursery
OOB	Out of Bag

PCA	Principal Component Analysis
PR	Plant-based energy Resources
RC	Recreation
RDA	Redundancy Analysis
RF	Random Forest
RP	Revealed Preferences methods
SDGs	Sustainable Development Goals
SHDI	Shannon's Diversity Index
SP	Stated Preference methods
TEEB	The Economics of Ecosystems and Biodiversity
TEV	Total Economic Value
UK NEA	United Kingdom's National Ecosystem Assessment

CHAPTER ONE

1 INTRODUCTION

"Nature is not a place to visit. It is home."

- Gary Snyder

1.1 Contextual background

Nature has been long known to provide ecosystem services (ES), such as food, water, disease management, climate regulation, spiritual fulfillment, and aesthetic enjoyment, to which humans depend on for their well-being and survival (Millennium Ecosystem Assessment, 2005). After Costanza et al. (2017), ESs are defined as "the functions and processes of ecosystems that benefit humans, directly or indirectly, whether humans perceive those benefits or not". However, as the human population grows, there is an increasing demand for food and energy resources. This continuing increasing trend, along with economic development, causes rapid and extensive alterations on ecosystems, resulting in the depletion of supplies (Guo et al., 2010). In addition, although humans and their activities are part of the global ecosystems, without the knowledge of the consequences that constant harvest of natural resources can cause, they may be irreversible effects on the ecosystems, which, in turn, risk human well-being. The ES framework is regarded as an effective communication tool to bridge the knowledge of science, policy-making and practice (Li et al., 2017b). In addition, mapping and assessing ESs represent important approaches towards understanding the link between ecosystems and human society, facilitating decision-making and management based on sustainable development strategies (Crossman et al., 2013; Egoh et al., 2008; Tallis et al., 2008). Such mapping should aim at providing quantitative aspects of the state of ecosystems (Maes et al., 2013). ESs are being studied from many perspectives, ranging from purely ecological or economic research to socio-ecological assessments. Possible ES applications are numerous: from sustainable management of natural resources, nature conservation, landscape and land use planning, climate protection to environmental education and research (Burkhard & Maes, 2017, p. 25). Thus, ESs have the potential to become a major tool for decision-making on global, national, regional and local scales.

All in all, while humans strongly depend on ES, their management decisions to benefit from natural resources have affected ecological integrity and biological diversity. A key challenge for ecosystem management is handling multiple ESs (Termorshuizen & Opdam, 2009), as certain actions enhance the supply of some ESs while inhibiting others (Bennett et al., 2009). Addressing this challenge requires the identification of the multiple and non-linear relationships among ESs to promote sustainable management in complex ecosystems and to achieve the constant supply of future ES. In addition, the identification of ES bundles allows interacting ESs to be managed coherently together instead of individually (Jaligot et al., 2019b). These interactions represent a synergy or a trade-off situation, where the use of one ES directly increases or decreases the supply of another service, respectively (Turkelboom et al., 2016). However, there is evidence that ESs act differently across both spatial and temporal scales (Qiu et al., 2018). This stems from the fact that land use/cover patterns affect the provision of ESs. In addition, ES interactions are not constant over time, resulting in temporal changes being overlooked in ES-based approaches, which might lead to the misrepresentation of their synergies, leading to future trade-offs (Renard et al., 2015; Tomscha & Gergel, 2016).

Another major challenge is to reverse the degradation of ecosystems while meeting increasing demands for their services (Millennium Ecosystem Assessment, 2005, p. 92). But this challenge can be met through raising awareness on the sustainable use of ES. This includes understanding the balance between the supply and demand for ESs as key towards elucidating how people and nature are linked. Supply refers to the capacity of ecosystems to provide services, whereas the need for ESs is represented by societal demand. When usage exceeds the capacity of ecosystems to provide services, the natural environment can be negatively affected, causing the depletion of ES supply and unfulfilled demand (Wolff et al., 2015). Compared to ES supply, human demand for ESs is less quantified. However, in the past decades, ES demand has received increasing attention to be integrated into ES assessments. By quantifying the spatial alignment between ecosystems and beneficiaries, it is possible to identify where ESs are used unsustainably and where it is sensible to invest in the maintenance of ESs (Lorilla et al., 2019). On that note, research on ES must aim to the mainstreaming into policies and practices in order to ensure the continuous supply of ES and associated benefits to humans (Egoh et al., 2012).

An effective way to ensure the sustainable management of ecosystems includes addressing the drivers that could cause ecosystem change. The Millennium Ecosystem Assessment (2005) defines drivers as natural or human-centered factors that directly or indirectly cause changes to an ecosystem; direct drivers clearly influence ecosystem processes, whereas indirect drivers influence ecosystem processes by altering at least one direct driver. Identifying the linkage between such drivers and ESs is a key step essential to manage sets of ESs (also known as bundles) and to predict their temporal dynamics under alternative policies (Mouchet et al., 2014). As a result, studies on the relationships between ESs and human well-being are recently gaining attention. However, most research related to ESs focuses on direct drivers, such as land use change or invasive species. Yet, effective management requires more attention to indirect drivers such as demographic, economic, sociopolitical, and cultural factors (Guo et al., 2010).

Moreover, although land use changes and socioeconomic factors have important effects on both the supply and demand for ESs, few studies have explored the drivers of ES supply and demand altogether (Sun et al., 2020). Lack of knowledge on the relations between ESs and human well-being traces to a failure of the scientific community to generate, synthesize and convey the necessary information to the non-experts. Therefore, understanding how different social and ecological factors shape the delivery of ESs is of primary importance to achieve effective landscape policy and management.

Island ecosystems are unique in terms of their biodiversity, physical environment and threat by various natural and anthropogenic factors. On a recent review article, (Balzan et al., 2018b) highlighted the importance of defining how cultural, provisioning and regulating services co-exist, and the role of island ecosystems in the delivery of these services. They also identified the knowledge gaps and suggested future research in island ES assessment (Figure 1.1). Some of their main findings were: (1) studies carrying out a biophysical quantification of island ESs were lacking, suggesting an important gap in knowledge, (2) studies that use spatial data to assess recurrence of island ESs across spatial and temporal scales are also lacking, suggesting that investigating island ES bundles is much needed in the island ES literature, and most importantly, (3) pressures that impact on one ecosystem were shown to affect other interrelated ecosystems. In parallel, multiple ecosystems appear to contribute to the delivery of specific island ES, justifying that integrated management approaches are essential for maximizing the potential of island landscapes to deliver ESs while reducing the effects of trade-offs.

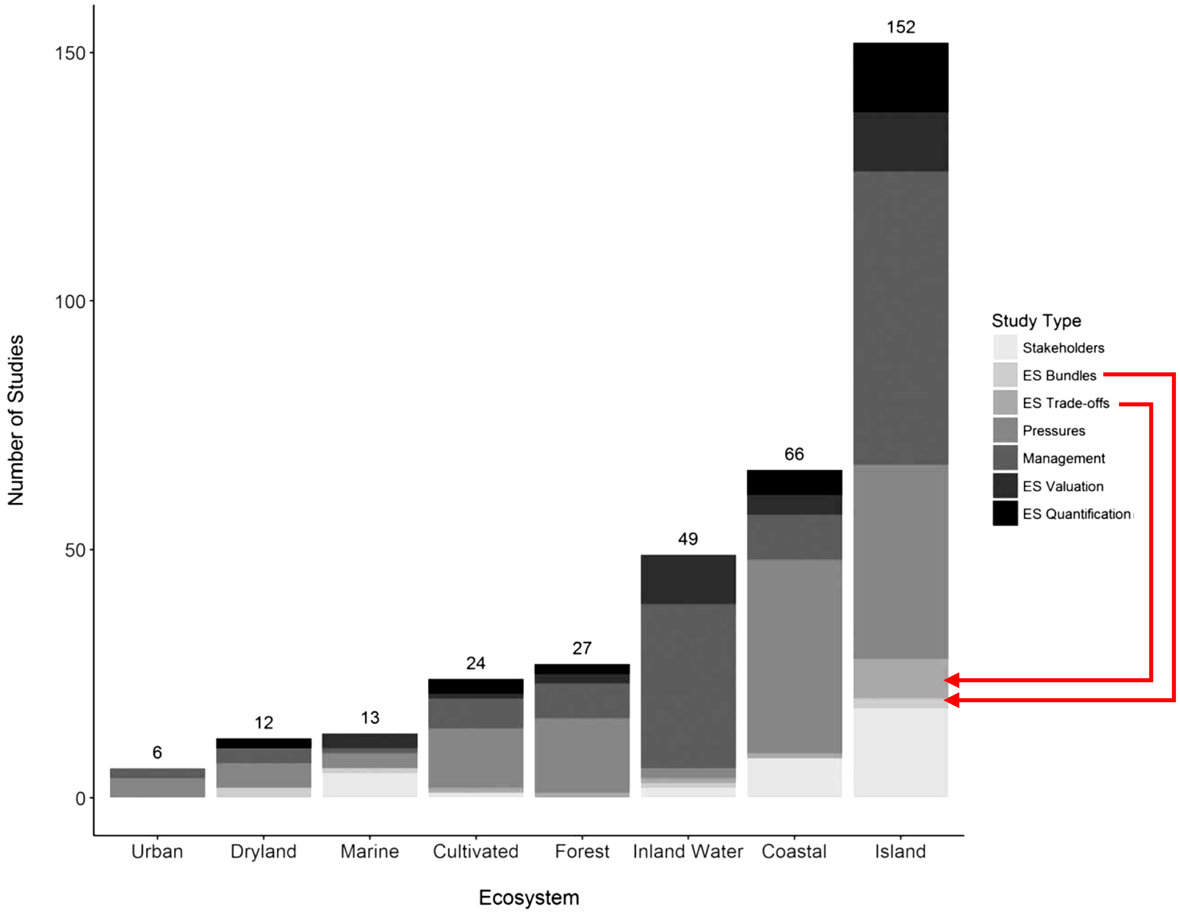

Figure 1.1: Number of ES studies in different ecosystems, where at the island scale there is a lack of studies on ES bundles and trade-offs. Source: Balzan et al. (2018b).

1.2 Objectives of the thesis and research questions

In line with the challenges mentioned above, the goal of this thesis is **to improve the understanding of ES occurrence and ES relationships** in complex and diverse Mediterranean ecosystems, such as those found in the Ionian Islands. This improved understanding **offers important information to decision-makers and landscape planners about the possible impacts that management decisions and actions could cause on sensitive ecosystems.** Specifically, this thesis aims **(1)** to assess the spatial dynamics and interactions among the supply of multiple ES, **(2)** identify the spatial congruence between the supply and demand of ES, and finally, **(3)** reveal the socio-ecological factors that determine the spatial distribution of ES bundles. According to the aims of this thesis, three main objectives are summarized, and five research questions (RQ) are formulated. These objectives and questions are addressed across the three main research chapters (Chapters three, four and five).

A. **Objective 1**: Assess the spatial and temporal interactions among multiple ESs.

To optimize future ES provision, information on the relationships among multiple ESs is essential. However, ES interactions are not constant over time, resulting in temporal changes being overlooked in ES-based approaches, which might lead to the misrepresentation of their synergies, leading to future trade-offs. Therefore, the research questions linked to Objective 1 are:

RQ 1. What are the patterns of synergies and trade-offs within ES bundles on Mediterranean island ecosystems?

RQ 2. How do ES relationships change across a temporal scale?

B. **Objective 2**: Identify the spatial congruence between ES supply and demand.

Understanding the spatial relationship between the supply and demand of ESs is a fundamental component in achieving sustainability and key towards elucidating how people and nature are linked. Additionally, to maintain the provision of multiple ESs, ESs must be consistently used under a sustainable regime that balances ES provision and societal demand. The research questions linked to Objective 2 are:

RQ 3. How well does the supply of ESs and demand by society spatially match?

RQ 4. How can land management and planning facilitate maintenance or optimization of the provision of ESs?

C. **Objective 3**: Reveal the socio-ecological determinants of the distribution of ES bundles.

The capacity for ecosystems to provide specific ESs depends on the interactions between biophysical characteristics and human presence. To support informed decision-making on landscape management, and implement appropriate planning actions, information on how different social and ecological factors shape the delivery of ESs is of primary importance. The final research question, which is linked to Objective 3, is:

RQ 5. Are the composition and the distribution of ES bundles more strongly shaped by social, economic or ecological factors?

1.3 Thesis outline

To address the research questions and objectives that are mentioned in the Introduction section (**Chapter one**), the chapters of this thesis are organized, starting from theory and basic concepts of ESs (**Chapter two**). Continuing, mapping, assessing and revealing temporal relationships among ESs (**Chapter three**), identifying spatial mismatches of ESs (Chapter four), and determining contributors of ES bundles (**Chapter five**) are presented. Finally, the thesis ends with the general conclusions of this thesis and some suggestions for future research (**Chapter six**) [Figure 1.2].

Chapter two addresses the history and concept of ESs, as well as the different definitions and classification systems that have been developed through the years. A literature review on the three main chapters is employed to present the state-of-the-art mapping, assessing and modeling approaches of ES studies, which formulated the research question of this thesis. In addition, the ES components that are consistently used throughout this thesis are explained. Some of them include ES supply and demand, ES interactions, synergies and trade-offs and ES bundles.

Chapter three presents the assessment and understanding of the spatiotemporal dynamics of ES supply and how these components interact across the Ionian Islands to optimize future ES provision and mitigate current trade-offs. Specifically, it includes the quantification of seven ES, covering all three ES sections (provisioning, regulating & maintenance, and cultural) of the Common International Classification of Ecosystem Services (CICES), as well as the analysis of their interactions at a temporal scale across the four prefectures of the Ionian Islands. ES interactions were investigated by analyzing ES relationships, identifying ES bundles (sets of ESs that repeatedly occur together across space and time), and specifying ES occurrence within bundles.

Chapter four focuses on identifying spatial similarities and mismatches between the biophysical capacity of ecosystems to provide benefits and societal needs. Specifically, this chapter reveals the spatial linkage between the supply and demand of three ESs (food provision, climate regulation, and recreation), and identifies zones where excess supply and demand occur on the Ionian Islands. A supply-demand ratio was used to reveal the spatial relationship between the supply of services and societal demand. Furthermore, a hot spot analysis was used to delineate zones with high connectivity and compactness, which could facilitate the prioritization of conservation areas. For zones where an unsustainable regime exists, ways on how to maintain or shift current spatial policies are suggested.

Chapter five aims to reveal the importance of socio-ecological factors in shaping ES bundles to manage natural resources efficiently and enhance human well-being. Specifically, the relationships among multiple ESs are explored, including their supply and demand indicators. Bundles of ESs are identified to distinguish regions in which supply and demand exhibit different characteristics. Furthermore, an ensemble machine learning method (Random Forest - RF) was used to identify the most important socio-ecological variables out of 17 tested that contribute to ES bundles.

Chapter six comprises the main findings, the implications of the results in the spatial planning processes, suggestions for future research and general conclusions. Particularly, this chapter discusses how the research findings contribute to the decision-making process to achieve sustainable landscape management, constant delivery of ES, and human well-being.

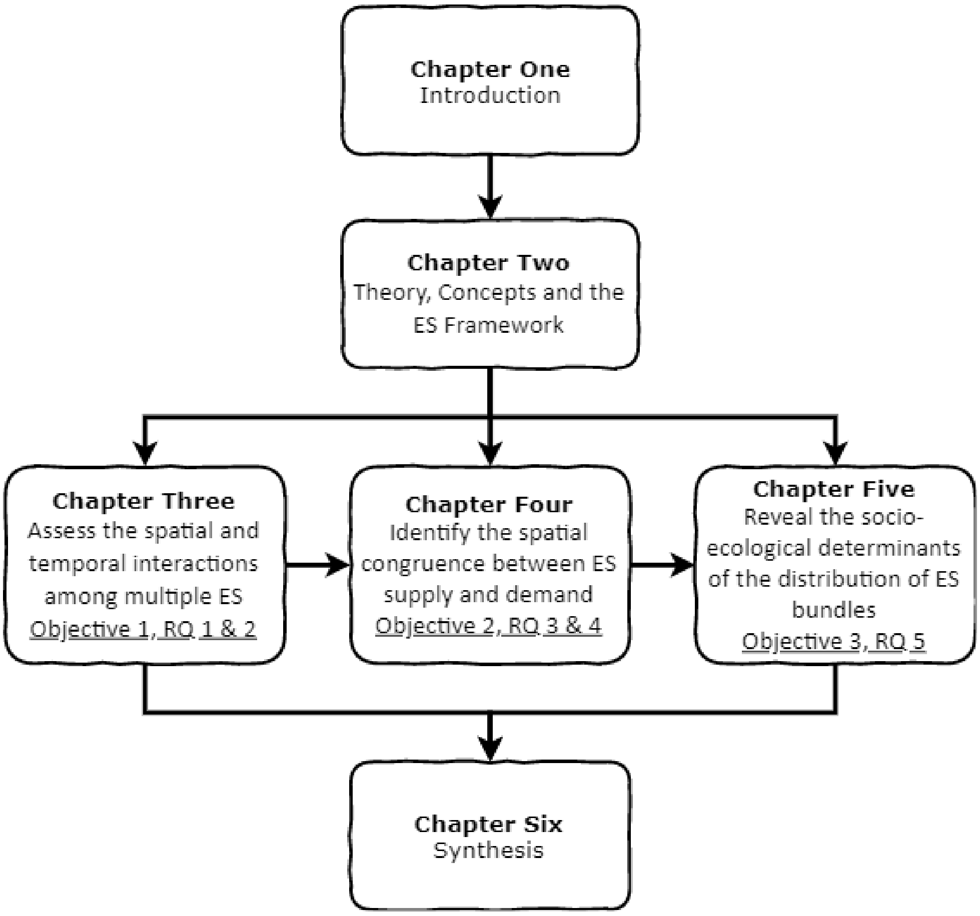

Figure 1.2: PhD thesis outline diagram. Source: own elaboration.

1.4 Study area

The study area encompassed the region of the Ionian Islands, which is located in the western part of Greece, south of the Adriatic Sea (Figure 1.3). In terms of administrative boundaries, the region consists of four prefectures, each of which contains a main Island and some islets. In 2011, the total population was 207,855 inhabitants (Hellenic Statistical Authority, 2014), which are mainly concentrated in urban and lowland regions (Lorilla et al. 2019). The region covers an area of 2278 km^2, wherein Corfu, Lefkada, Kefalonia, and Zakynthos cover 640, 355, 878, and 405 km^2, respectively. These Islands are characterized by high relief landscapes, with elevations reaching up to 1630 meters on Mountain Ainos.

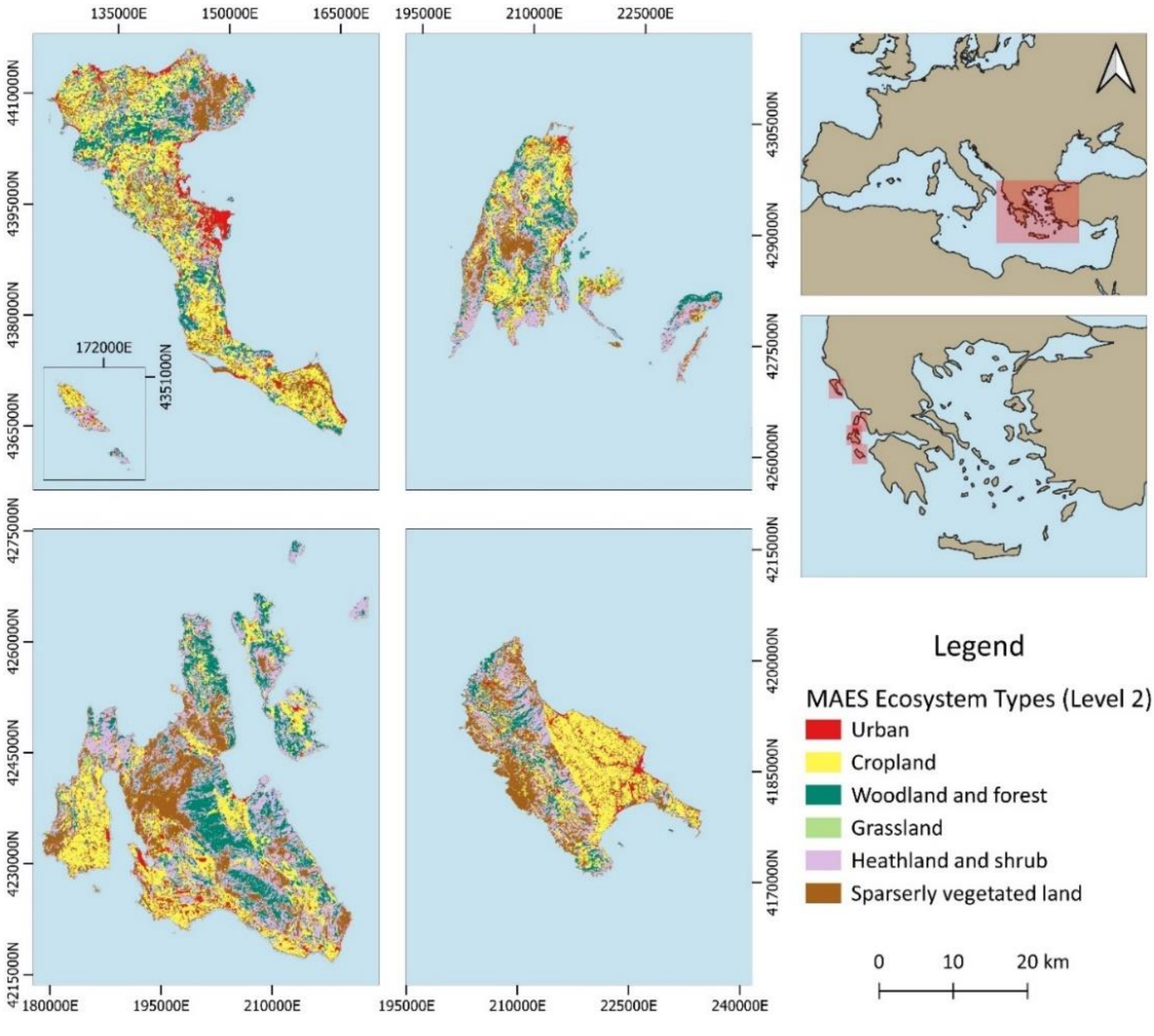

Figure 1.3: Location and vegetation categories of the Ionian Islands; land cover categorization is based on Maes et al. (2018b). Source: own elaboration.

The local climate is Mediterranean, consisting of mild–humid winters and warm–dry summers. Geologically, the islands of the Ionian Sea are situated on the outer margin of the thrust blocks that occupy the Greek Territory (Evelpidou, 2012). Lefkada, Kefalonia (including Ithaca), Zakynthos and Paxoi (islets included in the prefecture of Corfu) mainly consist of limestones, while the main island of Corfu is dominated by Neogene formations and Quaternary deposits (Evelpidou, 2012; Higgins, 2009).

Agriculture and tourism are among the most important sectors sustaining the economy of Ionian Islands (Courtis & Mylonakis, 2008; Gauci et al., 2013; Prokopiou et al., 2008; Prunier et al., 1993), where croplands, primarily olive orchards, cover approximately 42% total area of Corfu, 30% of Lefkada and Zakynthos, and 19% of Kefalonia (Kefalas et al., 2018). Despite intense human pressure (mass tourism, intensive agriculture, and frequent fire events), forests and woodlands occupy a large extent of the Ionian Islands [31% forested areas] (Kefalas et al., 2019). Other vegetation types, such as transitional and sparse vegetation (12, 11, 9 and 8% of Zakynthos, Kefalonia, Lefkada and Corfu, respectively) are also evident in the region (Kefalas et al., 2018).

The Ionian Islands encompass 14 protected areas under the Natura 2000 Network with natural characteristics and ecological features, such as the presence of nesting habitat for the loggerhead sea turtle *Caretta caretta* (Rees et al., 2017; Schofield et al., 2015). In addition, their coastal ecosystems consist of approximately 400 km^2 of seagrass coverage, the second-largest in Greek territory after the Southern Aegean region (Topouzelis et al., 2018). Overall, the Ionian Islands are characterized by diverse ecosystems, with high natural and cultural value, facilitating the delivery of ESs (Lorilla et al., 2018).

1.5 Publications

1.5.1 Scientific papers

1. **Lorilla, R.S.**, Poirazidis, K., Kalogirou, S., Detsis, V., & Martinis, A. (2018). *Assessment of the spatial dynamics and interactions among multiple ecosystem services to promote effective policy making across Mediterranean island landscapes.* Sustainability, 10(9), 3285. 10.3390/su10093285
2. **Lorilla, R.S.**, Kalogirou, S., Poirazidis, K., & Kefalas, G. (2019). *Identifying spatial mismatches between the supply and demand of ecosystem services to achieve a sustainable management regime in the Ionian Islands (Western Greece).* Land Use Policy, 88, 104171. 10.1016/j.landusepol.2019.104171
3. **Lorilla, R.S.**, Poirazidis, K., Kalogirou, S., Detsis, V., & Chalkias, C. (2020). *Socio-ecological determinants of multiple ecosystem services on the Mediterranean landscapes of the Ionian Islands.* Ecological Modelling, 422C, 108994. 10.1016/j.ecolmodel.2020.108994

1.5.2 Oral presentations including published abstracts

1. **Lorilla R.S.**, Poirazidis, K., Kalogirou, S. & Martinis, A. (2016). Synergies and trade-offs analysis of ecosystem services: the case of Ionian Islands. Proceedings of the 8th Congress of the Hellenic Ecological Society (Book of Abstracts). Aristotle University of Thessaloniki (Greece), 20 – 23 October 2016, p. 62 (in Greek)
2. **Lorilla R.S.**, Poirazidis, K., Kalogirou, S. & Martinis, A. (2016). Mapping and assessment of ecosystem services on Ionian Islands. Proceedings of the 9th Hellenic Congress of Hellas GIs (Book of Abstracts). National Technical University of Athens (Greece), 8 – 9 December 2016, p. 15 (in Greek)
3. **Lorilla R.S.**, Poirazidis, K., Kalogirou, S. & Martinis, A. (2017). Mapping and identifying areas of high value in provisioning ecosystem services. Proceedings of the 2nd Congress on GIS and Spatial Analysis in Agriculture and the Environment (Book of Abstracts). Agricultural University of Athens (Greece), 25-26 May 2017, p. 60-61 (in Greek)
4. **Lorilla R.S.**, Poirazidis, K., Detsis, V. (2019). Identifying the main explanatory variables of the supply and demand of multiple ecosystem services. Proceedings of the 3rd Congress on GIS and Spatial Analysis in Agriculture and the Environment (Book of Abstracts). Agricultural University of Athens (Greece), 11-13 December 2019, p. 55-56 (in Greek)

CHAPTER TWO

2 THEORY, CONCEPTS AND THE ECOSYSTEM SERVICE FRAMEWORK

"The most important contribution of the widespread recognition of ecosystem services is that it reframes the relationship between humans and the rest of nature."

- Costanza et al. (2014), Global Environmental Change

The origins of the modern history of ecosystem services (ESs) are to be found in the late 1970s (Gómez-Baggethun et al., 2010). Later, it was pushed to the background in the 1980s by the sustainable development debate (Burkhard & Maes, 2017, p. 31) but came back strongly in the 1990s with the mainstreaming of ESs in professional literature and with an increased attention to their economic value (Costanza et al., 1997; Daily, 1997). In 2005, the concept of ESs gained broader attention when the United Nations (UN) published its Millennium Ecosystem Assessment (MEA). It was then when the widely accepted definition of ESs appeared as "*the benefits people obtain from ecosystems*" (MEA, 2005, p. 40). Ever since, the definition has evolved so as to reflect varying concepts from an ecological or economic perspective. In addition to MEA, in 2010, the TEEB report entitled "*The Economics of Ecosystems and Biodiversity*" (de Groot et al., 2010; TEEB, 2010) was picked up extensively by the mass media, bringing ESs to an even broader audience (Costanza et al., 2014). Their definition of ESs followed the MEA definition with a finer distinction between services and benefits, which formed as "*the direct and indirect contributions of ecosystems to human well-being*". More recently, Burkhard & Maes (2017) became more specific and defined ESs as "*the contributions of ecosystem structure and function (in combination with other inputs) to human well-being*" (Burkhard & Maes, 2017, p. 25). In addition, Costanza et al. (2017) defined ESs as "*the functions and processes of ecosystems that benefit humans, directly or indirectly, whether humans perceive those benefits or not*". The links between people and nature are complex, and therefore, it is hardly surprising that people have referred to ESs in different ways (Burkhard & Maes, 2017, p. 41). Despite the establishment of different definitions, all imply that mankind is strongly dependent on well-functioning ecosystems and natural capital that are the basis for a constant flow of ESs from nature to society.

2.1 The concept of ecosystem services & the cascade model

Most ES literature are based on and influenced by the cascade framework (Figure 2.1) proposed by Haines-Young & Potschin (2010; 2013; 2018). The purpose of the cascade framework is to show the path way of ESs from ecological structures and processes to human well-being (La Notte et al., 2017). According to Potschin-Young et al. (2018), the model suggests that in order to understand the relationships between people and nature, we need to identify both the functional characteristics of ecosystems[1] that give rise to services and the benefits and values that they support. Furthermore, changes in benefits and values form the way people deal with the various drivers of ecosystem change. The five elements of the cascade are intended to encourage users to study the distinction between what are understood as services and benefits, and to examine the particular functional characteristics of ecosystems that create services, as opposed to the more general ecological structures and processes that support them (Potschin-Young et al., 2018).

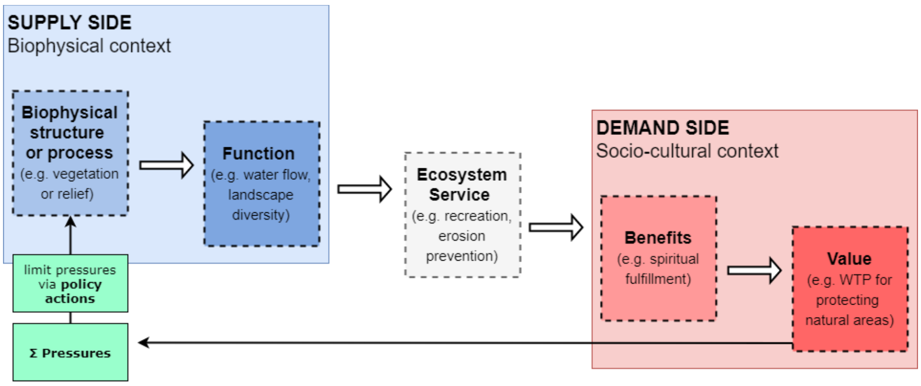

Figure 2.1: The ES cascade model/framework. Adapted from de Groot et al. (2010) and Haines-Young & Potschin (2010).

As Figure 2.1 depicts, ES are generated by ecosystem functions which in turn are underpinned by biophysical structures and processes (de Groot et al., 2010). Ecosystem functions are thus intermediate between ecosystem processes and services. Actual use of a service provides benefits which in turn can be valued in economic terms and monetary terms. For example, vegetation cover is a ***biophysical structure*** which helps to store carbon above and below ground (***function***). This function provides a service called climate regulation. This carbon regulation ***ecosystem service*** contributes to security and human health (***benefit***) through mitigating the effects of global warming. This benefit is valued according to how much money people are willing

[1] An ecosystem is broadly defined as a complex of living organisms (biotic) with their physical environment (abiotic), along with the interactions between these two components (Smith & Smith, 2006, p. 5).

to pay (WTP) to preserve this benefit (***value***). Therefore, the difference between an ES and a benefit is that benefits are the things that people assign value to (Burkhard & Maes, 2017, p. 42).

2.2 The categorization systems of ecosystem services

Since the publication of the book "*Nature's Services*" (Daily, 1997) and of an article in the Nature journal entitled "*the value of the world's ecosystem services*" (Costanza et al., 1997), a growing body of literature has emerged on classifying ESs. Ever since, a number of different typologies of ESs are available, including those used in the Millennium Ecosystem Assessment (MEA), The Economics of Ecosystems and Biodiversity (TEEB), the Common International Classification of Ecosystem services (CICES), and in a number of national assessments, such as those in the UK, Germany, Spain and the United States.

Each classification has its advantages and disadvantages due to the specific context within which they were developed (Maes et al., 2013). The MEA was the first large-scale ecosystem assessment, and it provides a framework that has been adopted and further refined by TEEB and CICES. The MEA organizes ESs into four well-known groups: (1) provisioning services, (2) regulating services, (3) cultural services and (4) supporting services. The TEEB report proposes a typology of 22 ESs divided into four main categories, mainly following the MEA classification: (1) provisioning services, (2) regulating services, (3) habitat services and (4) cultural & amenity services. Another similar classification of ESs is that of the United Kingdom's National Ecosystem Assessment (UK NEA, 2014), which classifies ESs along functional lines into the four categories (Figure 2.2).

Figure 2.2: ES categorization system according to UK NEA. Source: http://uknea.unep-wcmc.org /EcosystemAssessmentConcepts/EcosystemServices/tabid/103/Default.aspx.

The problem with the different typologies is that they all approach the classification of ESs in different ways, involving different scale perspectives and different definitions, resulting in the fact that they are not always easy to compare (Burkhard & Maes, 2017; Maes et al., 2013). Another problem that arose with the MEA classification came apparent in the National Ecosystem Assessment of Spain (SNEA). The SNEA followed the guidelines of MEA, however overlooked the category of supporting services mainly (a) for the confusion generated among services, functions and ecological functioning and (b) for the double counting problems associated with economic valuation (SNEA, 2014).

In order to partly overcome the problems, CICES was proposed in 2009 (Haines-Young & Potschin, 2010), revised in 2013 (Haines-Young & Potschin, 2013) and finalized in 2018 (Haines-Young & Potschin, 2018). CICES has been designed so that the categories at each level are not overlapping and have no redundancy. The categories at the lower levels also inherit the properties or characteristics of the levels above (Figure 2.3). As a result, CICES can be regarded as a strict classification with the following recommended definitional structure: (1) provisioning services, (2) regulating & maintenance services and (3) cultural services. Specifically, CICES offers a relatively high level of detail (the highest number of ES categories among the classifications already mentioned) in a hierarchical structure of taxonomical levels (Czúcz et al., 2018). Thus, in CICES, as we move successively from Section, through Division, Group and Class, the description of the service is progressively more specific and there may be many service types (Class type) nested within these broader categories (Haines-Young & Potschin, 2013).

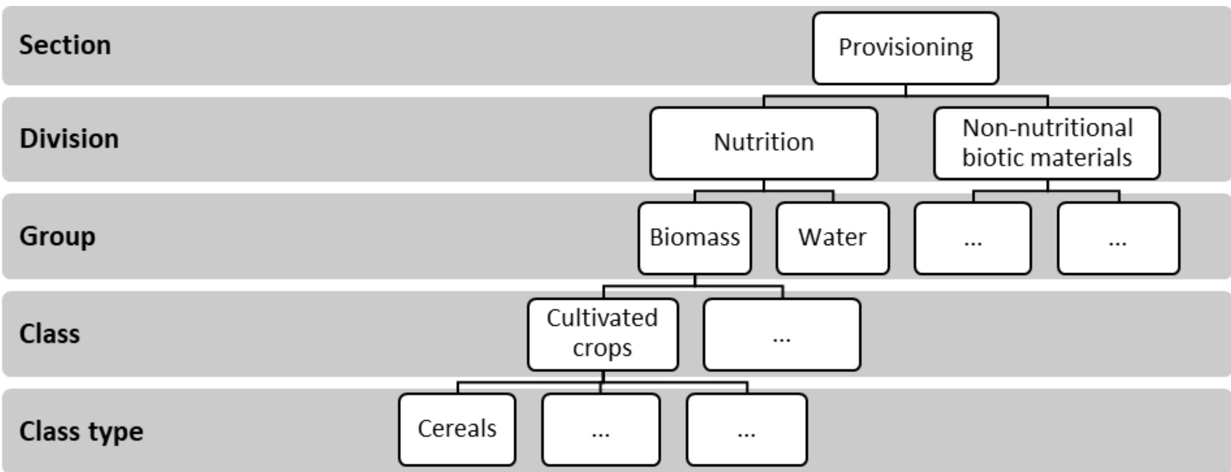

Figure 2.3: The hierarchical structure of the CICES. Adapted from Burkhard & Maes (2017) and Haines-Young & Potschin (2010).

The CICES framework has been widely adopted by the ES community, as it provides a flexible and hierarchical tool that may be adapted to the specific needs of the different regions (Haines-Young & Potschin, 2018; Kandziora et al., 2013). Two examples are the works conducted in Germany by Albert et al. (2015), and the United States Environmental Protection Agency (Landers & Nahlik, 2013). The German study recommended the development of national indicators for ESs, and the American study attempted to develop a classification system for final ESs, namely the National Ecosystem Services Classification System (NESCS). Other examples of the use of CICES in national ecosystem assessments are the ones conducted in Belgium (Turkelboom et al., 2013), Finland (Mononen et al., 2016), Germany (Grunewald et al., 2017), Greece (Kokkoris et al., 2018) and Switzerland (Jaligot et al., 2019c). Following CICES, this thesis takes into account three main categories of ES (Table 2.1) (Haines-Young & Potschin, 2013):

A. ***Provisioning services*** refer to all nutritional, material and energetic outputs from living systems. In the proposed structure a distinction is made between provisioning outputs arising from biological materials (biomass) and water.
B. ***Regulating and maintenance*** cover all the ways in which living organisms can mediate or moderate the ambient environment that affects human performance. It therefore covers the degradation of wastes and toxic substances by exploiting living processes. This category also covers the mediation of flows in solids, liquids and gases that affect people's well-being as well as the ways living organisms can regulate the physico-chemical and biological environment of people.
C. ***Cultural services*** cover all the non-material, and normally non-consumptive, outputs of ecosystems that affect physical and mental states of people. They include aesthetic inspiration, cultural identity, sense of home, and spiritual experience related to the natural environment.

Table 2.1: CICES at the three-digit level. Source: Haines-Young & Potschin (2013).

SECTION	DIVISION	GROUP
PROVISIONING	Nutrition	Biomass
		Water
	Materials	Biomass, Fiber
		Water
	Energy	Biomass-based energy resources Mechanical energy

Table 2.1: (Continued).

SECTION	DIVISION	GROUP
REGULATING AND MAINTENANCE	Mediation of waste, toxics and other nuisances	Mediation by biota
		Mediation by ecosystems
	Mediation of flows	Mass flows
		Liquid flows
		Gaseous / air flows
	Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection
		Pest and disease control
		Soil formation and composition
		Water conditions
		Atmospheric composition and climate regulation
CULTURAL	Physical and intellectual interactions with ecosystems and land-/seascapes [environmental settings]	Physical and experiential interactions
		Intellectual and representational interactions
	Spiritual, symbolic and other interactions with ecosystems and land-/seascapes [environmental settings]	Spiritual and/or emblematic
		Other cultural outputs

2.3 Mapping and quantification of ecosystem services

Many ESs face spatially explicit pressures or depend on anthropogenic contributions such as technology and energy (Syrbe et al., 2017, p. 151). The EU Biodiversity Strategy to 2020 called on member states of the European Union (EU) to map and assess the state of ecosystems and their services in their national territory (Action 5). In response to this requirement, an EU initiative on Mapping and Assessment of Ecosystems and their Services (MAES) was launched and a dedicated working group was established with Member States, scientific experts and relevant stakeholders.

Multiple components play a role in the provision and use of ESs, which can be mapped, assessed and monitored using quantitative indicators or qualitative estimations. ES mapping and assessment include defining particular ecosystem properties and conditions, which in turn need to be identified in an ES-related approach. The supply of ESs is the basis of an ES mapping assessment as it refers to the capacity of a particular area to provide a specific set of services within a given time period (Burkhard et al., 2012); additionally, the amount of ES supply depends on natural conditions and often on human inputs, such as land management contributions, knowledge and technology (Syrbe et al., 2017, p. 154). The level required or desired by human society or individual preferences for specific ESs defines as the ES demand (Wei et al., 2017a).

Demand depends on several factors such as culturally-dependent desires and needs, availability of alternatives, or means to fulfil these needs (Syrbe et al., 2017, p. 156). As demand links ESs to beneficiaries, without it there is no flow. Therefore, ES flow is considered as the service that is actually received by people, and is measured directly as the amount of a service delivered, or indirectly as the number of beneficiaries served (Villamagna et al., 2013). On that note, ES flow is the spatial connection between areas of ES supply and areas of ES demand (Fisher et al., 2009; Verhagen et al., 2017).

ES maps are important tools for decision-makers and institutions, enabling them to identify which areas should be maintained due to their high supply of ESs (Balvanera et al., 2001). Maes et al. (2012a) provided some good reasons for mapping ESs to support decision- and policy-making, namely, evaluation of spatial congruence with biodiversity, analyzing synergies and trade-offs between different ESs, analyzing trends in ESs, estimating costs and benefits, comparing ES supply with demand, monetary valuation on biophysical quantities or the prioritization of areas in spatial planning and management. Additionally, Hauck et al. (2013) presented the benefits of ES maps drawn from the results on interviews and from a focus group discussion on regional, national and EU levels. Their findings on the potential benefits of ES maps for decision-making and support at different levels are summarized below:

- ✓ ES maps are useful in identifying conflicts and synergies between ESs or between ESs and other land uses.
- ✓ ES maps can indicate places or areas where particular ESs or aspects of biodiversity are threatened.
- ✓ ES maps can be helpful in identifying suitable policy measures, improving the targeting of such measures (e.g. by identifying hotspots), and demonstrating or evaluating the benefits of policy measures in relation to their costs.
- ✓ ES maps can communicate the relevance of biodiversity, ecological processes, and ESs to the public, and therefore are a powerful communication tool.
- ✓ ES maps can help to communicate to stakeholders and beneficiaries of services the impact of certain policy decisions and to make them more transparent.

ES mapping can be highly rewarding in terms of impact on real-world decision-making (Burkhard & Maes, 2017, p. 177). For these reasons, ES maps are often suggested as an essential means for analyzing the spatial configuration of multiple ES in both regional and landscape levels (Hauck et al., 2013). Therefore, ES mapping is a useful tool for guiding land use planning and decision-making for management at large scales, where multiple sectors, such as agriculture, urban areas, water resources, conservation and forestry intersect (Malinga et al., 2015).

2.3.1 Mapping methods of ecosystem services

Given the importance of ES maps, the number of studies mapping ESs has grown exponentially. As a result, several reviews on ES mapping have been published to better understand the type of data, indicators and methods used in ES studies. There are different approaches on how to classify the different methods for ES mapping. The first attempt on reviewing ES studies came from Martínez-Harms & Balvanera (2012), whose classification of mapping methods was later used by Burkhard & Maes (2017), where five groups of methods to mapping ESs were determined:

1. **Look-up tables**: Use of existing studies to link ESs to land-cover classes.
2. **Expert knowledge**: Potential of land use/cover types to provide specific ESs based on experts ranking procedures.
3. **Causal relationships**: Incorporate existing knowledge on different layers of information related to ecosystem processes and services to create a new ES proxy.
4. **Extrapolation of primary data**: Field data databases weighted by cartographical data (usually land cover).
5. **Regression models**: Employing empirical- or statistical-based models are able to calculate ES values, given other input variables. Using field data of ESs as response variables and other proxies, such as biophysical data, as explanatory variables.

The review period of Martínez-Harms & Balvanera (2012) expanded from 1995 to 2011. Since then, many more review studies emerged in the ES literature. For example, Götzl et al. (2013) classified applied mapping methodologies in three categories: (1) quantitative modelling analysis and mapping based on collecting primary data, (2) quantitative modelling analysis using existing data, and (3) expert knowledge and literature findings. Their categorization was clearly based on the type of data sources, however, this classification did not present specific methods of quantification and mapping ESs. Three categories of mapping methods were also identified in the Joint Research Centre's (JRC) Scientific and Policy Report entitled "*Indicators for mapping ecosystem services: a review*" by Egoh et al. (2012), who classified methods of ES mapping based on the quantification of indicators. In particular, they presented an overview of quantification methods under three groups: (1) collection of primary data through direct observations, (2) proxy methods in which a single or combined indicators are used to define ESs, and (3) process models in which indicators are used as variables in the equation. Crossman et al. (2013) with no specific categorization system reviewed and presented results of studies mapping ESs for each category and type of ESs to provide a blueprint, including a template and checklist of information, needed for those beginning an ES modelling and mapping study. Similarly, Malinga et al. (2015) reviewed ES mapping literature in respect to spatial scale, world distribution, and types of ESs considered.

Some of the above-mentioned categorization systems of mapping methods clearly refer to the supply of ESs, despite the increasing interest in the demand for a wide range of ESs. To address the general issue of the few assessments, on the demand-side of ESs, and not only in review studies, Wolff et al. (2015) collected ES studies to provide an overview of the available approaches to map the demand for ESs. Their study, which was conducted up until July of 2014, identified 31 studies that have mapped demand, whereas in 2011, Martínez-Harms & Balvanera (2012) had already found 95 ES supply mapping studies. In the surveyed literature search of Wolff et al. (2015) five groups of methods for mapping ES demand were distinguished:

1. **Empirical methods**: qualitative and quantitative research methods to gain understanding by observation and data acquisition.
2. **Participatory approaches**: direct assessment of preference and values to quantify demand of stakeholders, experts or users.
3. **Expert based approaches**: approaches using knowledge of experts, often supported with information from literature and secondary data.
4. **Process based models**: models based on the theoretical understanding of ecological processes.
5. **Monetary valuation**: calculation of the monetary value of ESs.

Without distinguishing ES supply and demand, a recent review studies by Andrew et al. (2015) categorized ES studies in six groups: (1) Direct mapping, (2) Empirical models, (3) Simulation and process models, (4) Logical models, (5) Extrapolation methods and (6) Data integration methods. Following this categorization system, Englund et al. (2017) added two additional method types refering to (7) Combination methods and (8) Unknown. It is clear that ESs is a significant research topic with diverse modelling and mapping approaches. However, the variety of approaches, along with an inconsistent terminology, cause uncertainties concerning the choice of methods.

2.3.2 Ecosystem service indicators

The most important consideration of any ES mapping study is the purpose, the audience, its position on the ES cascade, the spatial and temporal scale considered and the availability of data (Vihervaara et al., 2017, p. 96). Defining these is critical and must be determined before starting to implement a specific mapping method. For example, Martínez-Harms & Balvanera (2012) found that readily available data were the most frequently used over primary data. In addition, their findings indicated that biophysical data (often land-cover variables) and mixed sources, such as statistic databases, were most commonly employed. Similarly, Burgess et al. (2016) and Egoh et al. (2012) found that indicators and proxies are the most commonly used methods for mapping natural capital and ESs.

To overcome the diversification between different systems of ES mapping methods, the MAES working group developed an analytical framework (1st report) to ensure that consistent approaches are used throughout the EU (Maes et al., 2016). In connection with the different categorization systems of ESs (see section 2.1.2), the MAES framework uses CICES as the basis for classifying ESs. In 2014, a 2nd technical report of the MAES working group was issued, which proposed indicators that can be used at European and Member State's level to map and assess ESs (Maes et al., 2014). From a total of 1118 potential indicators, 327 indicators, covering different types of ecosystems, were used to develop a set of indicators for the assessment of ESs (Maes et al., 2016). Such ES indicators have the potential to provide "*information that efficiently communicates the characteristics and trends of ESs, making it possible for policy-makers to understand the condition, trends and rate of change in ESs*" (Vihervaara et al., 2017).

ES indicators can be quantified through biophysical and economic quantification, socio-cultural valuation, computer modelling and application of expert knowledge (Burkhard & Maes, 2017). It is clear that there is an abundance of methods for mapping, quantifying, valuation and assessment of ESs. ES supply outcomes are usually expressed in terms of biophysical indicators, while ES demand outcomes are expressed in terms of preferences, perceptions, or economic values (Sun et al., 2020). This thesis employed biophysical indicators and models, and economic quantification methods, which will be presented and further discussed in the following section.

2.3.3 Biophysical quantification

The biophysical quantification methods are based on quantification of different parameters of biotic and abiotic structures which determine the provision of ESs (Vihervaara et al., 2018). ES biophysical indicators are divided into three main categories in relation to the character of the measurements and how the necessary information is extracted (Vihervaara et al., 2018). These include (1) direct measurements, (2) indirect measurements and (3) biophysical (numerical) models.

1. Direct measurements of ESs is the actual measurement of a state, a quantity or a process from observations, monitoring, surveys or questionnaires which cover the entire study area in a representative manner. Direct measurements are also used as primary data to other methods, as they are one of the most accurate ways to quantify ESs. Examples of direct measurements are crop, livestock and water statistics, site or field observations and surveys, or measurements of forests stands, soil erosion etc. However, although such measurements are the most accurate way to quantify ESs, they are time and resource consuming and thus, costly and impractical. Therefore, the next step is to consider for biophysical quantification through indirect measurements.
2. Indirect measurements of ESs deliver a biophysical value of ES in physical units which are different from the units of the selected indicator. For example, variables can be collected through remote sensing. Additionally, the density of roads, trails or camping sites can provide an indicator of ESs. Therefore, such variables need further interpretation, certain assumptions or data processing, or they need to be combined in a model with other sources of environmental information before it can be used to measure an ES.
3. ES modelling methods can be used to quantify ESs if no direct or indirect measurements are available. Models can vary from simple expert-based scoring systems to complex ecological models, such as planetary cycles of carbon, nitrogen and water. For example, expert knowledge can be used to apply weights of importance to multiple GIS layers to produce a specific ES.

2.3.4 Economic valuation

The seminal work by Costanza et al. (1997) have triggered the need of researchers and public authorities to evaluate the relative importance of all types of ecosystems in terms of their economic attributes. Economic quantification or valuation is one way to assess and communicate the importance of ESs to decision-makers and can be used in combination with other forms of information (Brander & Crossman, 2017, p. 115). Economic quantification of ESs attempts to measure the human welfare derived from the use or consumption of ESs usually measured in monetary units. Also, expressing ES values in monetary units provides guidance in understanding user preferences and the relative value current generations place on ESs (de Groot et al., 2012). The concept of Total Economic Value (TEV) is used to describe the comprehensive set of utilitarian values derived from an ecosystem. This concept is useful for identifying the different types of values that an ecosystem provides.

The types of ES values fall into two main categories: use and non-use values. Use values can be associated with private ESs, for which market prices usually exist, and can be divided further into two categories: (a) direct use value, related to the benefits obtained from direct use of ESs and (2) indirect use values, associated with regulating services, such as air quality regulation or erosion prevention, which can be seen as public services, and which are generally not reflected in market transactions (Pascual et al., 2012, p. 15). Whereas, non-use values are those values that do not involve direct or indirect uses of ESs but reflect satisfaction that individuals derive from the knowledge that biodiversity and ESs are maintained (Pascual et al., 2012, p. 15). Depending on the value type and the estimated ES, the appropriate valuation methods should be selected (Table 2.2), as different approaches may produce diverse results.

Table 2.2: Correspondence between ESs and components of TEV. Source: Vihervaara et al. (2018).

ES	**TOTAL ECONOMIC VALUE**			
	Direct use	Indirect use	Option value	Non-use
PROVISIONING	×		×	
REGULATION AND MAINTENANCE		×	×	
CULTURAL	×		×	×

There are three main groups of economic valuation methods: (1) Direct market valuation approaches (DM), (2) Revealed preferences methods (RP) and (3) Stated preference methods (SP) [Table 2.3] (Pascual et al., 2012). DM valuation approaches use data from actual markets, and thus reflect actual preferences or costs to individuals, which are relatively easy to obtain. However, due to some ESs not having markets when applied results may deviate actual market behavior. RP methods are based on actual market behavior of users of ESs. However, their applicability is limited only to a few ESs. In addition, market imperfections and policy failures can as well distort the estimated monetary value of ESs if revealed preferences methods are used. SP can be used to estimate both use and non-use values of ESs. SP approaches simulate a market and demand for ESs by means of surveys (usually questionnaires) on hypothetical changes in the provision of ESs. The main disadvantages of SP are that they are based on hypothetical situations and questionable preferences of respondents making their application complex and resource consuming.

Table 2.3: Overview of economic valuation methods. Adapted from Daly Hassen (2016) and Pascual et al. (2012).

METHOD GROUP	VALUATION METHOD	BENEFITS OF METHOD	LIMITATIONS OF METHOD
DIRECT MARKET VALUATION	Market price	Market data are available and robust	Only available for market services, i.e. goods
	Cost-based*	Market data are available and robust	Potentially overestimated actual value
	Production-based	It relates to objective measurements of biophysical parameters.	Data on the cause-effect linkages between the valued ES and the market are lacking
REVEALED PREFERENCES METHODS	Hedonic pricing	Based on market data	Very data intensive and limited mainly to property-related data
	Travel cost	Based on observed behavior	Limited to recreation and problematic for multiple destination trips
STATED PREFERENCE METHODS	Contingent valuation	Able to capture all use and non-use values	Potential bias in response, hypothetical market (not observed behavior), resource-intensive
	Choice experiment	Able to capture all use and non-use values	Potential bias in response, hypothetical market (not observed behavior), resource-intensive

*The category of cost-based methods considers all three approaches of damage cost avoided, replacement costs and substitution costs, which are equally applicable.

In cases where decision-making requires information quickly and at low cost, the benefit transfer approach is an alternative to valuation methods (Richardson et al., 2015). The benefit transfer method involves transferring monetary values of ES in a specific study area and applying them to another one, assuming that similarities exist between the selected areas in terms of the socio-economic context and the characteristics of their natural environment (Tammi et al., 2017). There are doubts about the reliability of benefit transfers (Navrud & Ready, 2007; Plummer, 2009; Rosenberger & Stanley, 2006), but the consensus remains that benefit transfer will continue to play a role in environmental policy analysis because of the lack of resources in governmental land management agencies (Boutwell & Westra, 2013). Therefore, while benefit transfer is an expedient way of producing estimates of economic values when primary, site-specific data are lacking, it will always be considered as a "second-best" valuation method (Plummer, 2009).

Employing one or the other method will depend on the objectives of the study and of the degree of familiarity with the different methods. The final selection of the method depends on many factors, such as the type and number of objects (i.e. ESs) to be valued, the relevant population (users or non-users or both, the geographical scope (local, regional, national, international), the data availability, the available time and financial resources, and the experience of the research team.

2.4 Ecosystem service associations

Much research has focused on how a single ES is supplied by certain ecosystems or demanded by certain groups of people. However, in reality, ecosystems or landscapes and their biodiversity provide multiple ESs which also influence each other (Turkelboom et al., 2016). The MEA (2005) has raised the awareness of the importance of identifying multiple ESs and the relationships among them. Ignoring the multifunctionality[2] of land systems in natural resource management can generate potential trade-offs with respect to the delivery of ESs. In addition, as ESs ultimately depend on the ecological functions within ecosystems, a good knowledge of the underlying processes can indicate where trade-offs are likely to occur (Howe et al., 2014). Understanding

[2] Landscape multifunctionality defines as "*the capacity of a landscape to provide socio-economic and ecological benefits to society, including potential trade-offs and synergies between individual ecosystem functions and services*" (Hölting et al., 2019).

the relationships between ES can therefore facilitate the mitigation of undesired trade-offs and enhance synergies (Lee & Lautenbach, 2016).

Once ESs have been quantified, spatial or temporal trends in the distribution of two or more services can be compared to find significant associations among ESs (Mouchet et al., 2014). Two mechanisms may lead to associations among ES; one being the supply of several ES that relies on the same ecosystem process, and the other referring to a given external factor that may affect several ESs at the same time (Bennett et al., 2009). In the first case, the capacity of an ecosystem to supply multiple ESs stems from linkages among basic processes, while, in the second case, the way one service is managed, in order to enhance it, will likely affect one or more other services (Mouchet et al., 2014). As a result, some ES co-vary positively, while others co-vary negatively. In general, relationships among ESs can be categorized into synergies, trade-offs and no-effect (Lee & Lautenbach, 2016). When two services co-vary in the same direction (positively), the relationship is defined as “synergistic” (Bennett et al., 2009) or “win-win” (Howe et al., 2014). Whereas, a situation to which one service responds negatively to a change of another service, the relationship is called “trade-off” (MEA, 2005). When there is no interaction between services, the ES relationship is defined as “no-effect” (Lee & Lautenbach, 2016). Ecosystem management strategies aiming at enhancing the supply of specific services in a sustainable manner need to consider such linkages to ensure the provision of multiple ESs (Bennett et al., 2009; Cord et al., 2017; Qiu et al., 2018).

Given the increasing interest, research on the associations among ESs has been gaining ground in the scientific community, also resulting in the increase of several reviews addressing the different aspects of relationships between ESs (Cord et al., 2017; Howe et al., 2014; Lee & Lautenbach, 2016; Mouchet et al., 2014). Mouchet et al. (2014) proposed a guideline to investigate the relationships (or associations) among ESs, which included three successive steps: (1) detecting ES associations, (2) identifying ES bundles, and (3) exploring potential drivers. Similarly, Howe et al. (2014) analyzed ES relationships, but with a focus on users and beneficiaries of ESs. On a methodological perspective, Lee & Lautenbach (2016) performed a quantitative review of relationships between ESs with respect to the dominant relationships of ESs, the influence of scale at which the relationship was identified, and the effect of the selected method used for revealing the relationship. Their findings revealed that synergistic relationships were likely to be found among regulating services, and among cultural services, whereas trade-offs relationships were dominant between regulating and provisioning services. In addition, the regional scale was the most commonly used in ES assessments (Cord et al., 2017), probably due to the potential of regional studies in facilitating decision-making in implementing environmental management policies (Le Clec'h et al., 2018).

To guide researchers towards more systematic analyses of ES relationships, Cord et al. (2017) identified four prevalent research objectives of studies on ES synergies and trade-offs, namely (1) the identification and characterization of co-occurrences of ES, (2) the identification of drivers that shape ES relationships, (3) the exploration of biophysical constraints of landscapes and limitations to their multifunctionality, and (4) the support of environmental planning, management and policy decisions. More recently, Hölting et al. (2019) presented the strengths and limitations of current ES approaches that focus on multifunctional landscapes. In agreement with Cord et al. (2017), Hölting et al. (2019) believe that comprehensive analyses of relationships among ESs may provide the base for the implementation of sustainable management and planning strategies. Therefore, to be able to support management decisions, we need to identify drivers and underlying mechanisms that guide ES relationships and develop a complete understanding of complex socio-ecological systems. However, the majority of ES studies that assess trade-offs and synergies are not explicitly identifying the drivers and mechanisms underpinning relationships between ESs (Dade et al., 2019).

2.4.1 Detecting relationships among ecosystem services

ES studies have taken two different approaches to assess the spatiotemporal relationships among ESs: (1) the evaluation of associations at a given location and time, and (2) the evaluation of associations across sites and through time. The latter is considered as most sufficient when it comes to concluding that observed associations can be generalized to a larger extent (Mouchet et al., 2014). This case relates to the framework that was developed to identify ES bundles (Raudsepp-Hearne et al., 2010).

The first step to investigate associations among ESs is analyzing pairwise relationships between them. The most straightforward approach to reveal positive or negative direction of ES relationships is using graphical methods (Figure 2.4) such as comparing maps visually [or analysis of hotspots] (Morelli et al., 2017), detecting trends in trade-off curves (Elmqvist et al., 2011; King et al., 2015; Lang & Song, 2018), or star plots [also known as flower plots, rose diagrams and spider diagrams] (Queiroz et al., 2015; Raudsepp-Hearne et al., 2010; Turner et al., 2014). These visualization methods, however, do not necessarily provide information on the strength of the relationship among ESs (Mouchet et al., 2014). Pairwise correlation coefficients, on the other hand, are a popular method for quantifying the strength and the direction of the ES associations, and when it comes to revealing possible synergies or trade-offs, a simple correlation is a go-to choice.

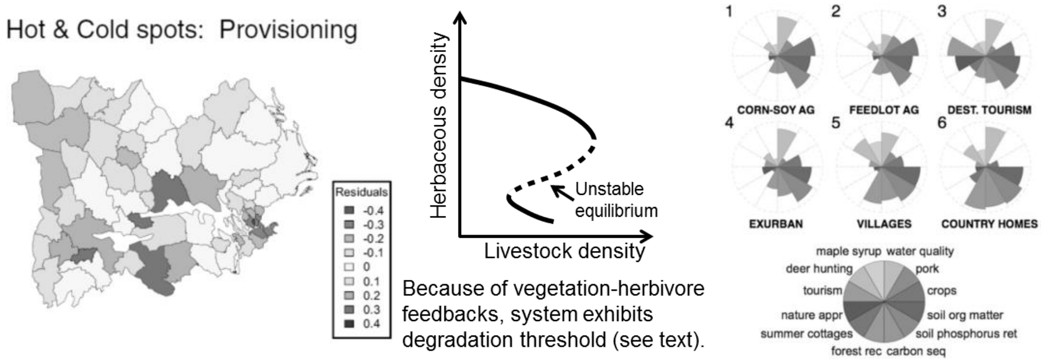

Figure 2.4: Examples of visualization methods to explore synergies and trade-offs among ESs; left: hotspot analysis of provisioning ESs in Queiroz et al. (2015); middle: trade-offs curve between livestock and herbaceous vegetation in King et al. (2015); right: star plots of ES bundles in Raudsepp-Hearne et al. (2010).

In the ES literature, correlations among services have been tested in different ways, which depend on the type of data to be compared. Note that Spearman's correlation test (against Pearson's) is mostly used, as ESs are quantified with a diversity of indicators, and so normal distribution is not always ensured. In the case of categorical data, chi-squared can replace the correlation analysis when the perceptions (Casado-Arzuaga et al., 2013; Molla & Mekonnen, 2019) or characteristics among users (Agwu et al., 2018) or the scale to which ESs are demanded [local vs. non-local] (García-Nieto et al., 2013) are to be investigated. When more than two ESs are being tested, a better alternative to correlation tables is multivariate analyses. These methods include Principal component analysis (PCA) for quantitative ESs, Multivariate Correspondence Analysis (MCA) for binary or nominal ES data (i.e., qualitative), and Factorial Analysis for Mixed Data (FAMD) for a combination of quantitative and qualitative data (Mouchet et al., 2014). Among these, due to the nature of ES indicators (mostly continuous type of data), PCA has been widely used to investigate ES synergies and trade-offs and/or to identify ES bundles in different country/regions (Chawanji et al., 2018; Depellegrin et al., 2016; Haida et al., 2016; Marsboom et al., 2018; Nikolaidou et al., 2017). Similar to chi-squared, MCA has been employed to determine the synergies and the trade-offs among multiple users of ESs (Trevisan et al., 2016) and their perception of restoring ESs (Hossu et al., 2019). ES associations can also be detected with the use of regression-based methods (Mouchet et al., 2014). Their use, however, extends beyond a simple correlation to implying possible causality; thus, to date, ES studies on simply identifying ES relationships with regression models are lacking (however, see section 2.3.3 for identifying drivers of synergies and trade-offs among ESs).

For a more spatially explicit method for the detection of ES associations, overlap analysis can quantify congruence or co-occurrence of ESs in a given area. For supply-supply situations (comparison between supply indicators), this is a standard method similar to hotspot analysis, where high values of ES supply are identified (Santarém et al., 2020; Villoslada Peciña et al., 2019). Also, when congruence or mismatch between ES supply and societal demand are to be investigated, the spatial overlap analysis is used (Sun et al., 2019). More on this topic is described in section 2.5. Lastly, natural processes tend to vary over temporal and spatial scales, and the ESs that they provide are, therefore, also highly variable (Koch et al., 2009). As a result, temporal relationships among ESs have been gaining increasing attention. A simple way to measure the differences of ES through time is by quantifying and comparing the supply of ESs among different years (Holland et al., 2011). In cases where ESs vary seasonally or along multiple years, time-series analyses may help determine the temporal variability of ES provision or relationships (Renard et al., 2015; Vargas et al., 2019).

On the dominant relationships among different ESs, Lee & Lautenbach (2016) compiled a comprehensive matrix of the ES relationships reported on the ES literature. Their main findings constitute the synergistic relationship between regulating services (case a), the trade-offs between provisioning and regulating services (case b), the synergistic relationship between cultural services (case c), and relationships with no effect between cultural and provisioning services (case d). However, as opposed to the latter case (case d), Qiu et al. (2018) and Rodríguez et al. (2006) reported strong negative correlations between cultural and provisioning ESs. Similarly, in changing Mediterranean landscapes, stakeholders clearly perceived the trade-off between provisioning services and cultural and regulating services (Martínez-Sastre et al., 2017). In the case of Mediterranean islands however, Balzan et al. (2018a) demonstrated synergic relationships between provisioning and regulating ES, unlike the general trend of them following a trade-off relationship (case b).

2.5 Identifying bundles of ecosystem services

The different biomes and ecosystems that cover the earth’s surface deliver various ES bundles at different quantities and qualities (Burkhard & Maes, 2017: 89). An ES bundle refers to a set of interacting (positively or negatively) ESs that repeatedly and simultaneously occurs across a spatial and temporal scale (Bennett et al., 2009). Although this definition had appeared before the first studies of spatially identifying ES bundles, the term "*bundle*" has been used in different ways following either an ES relationship-based definition ["*sets of consistently associated ecosystem services*"] or a space-based definition ["*sets of ESS provided by a specific location or ecosystem*"] (Saidi & Spray, 2018). Except for these two dominant definitions, other more versatile and diverse meanings started to appear as the number of publications of ES bundles began to increase. Some of them defined ES bundles as (Saidi & Spray, 2018):

- "*hotspots of ESs*"
- "*group of positively associated ES pairs*"
- "*set of ESs perceived by a specific group of people*"

Raudsepp-Hearne et al. (2010) first introduced the concept of identifying interactions among ES by analyzing the spatial pattern of ES bundles, with this concept being subsequently implemented by many researchers and on a variety of landscapes (Table 2.4). Their study became the most significant piece of work in analyzing ES associations through ES bundling. The ability of such a framework to pinpoint major issues, such as identifying opportunities for improved management or possible impacts of management decisions, has been triggering a growing amount of studies. Saidi & Spray (2018) conducted a systematic review and identified 51 studies that detected ES bundles as sets of consistently associated services falling under three categories: Mapping studies, Experimental studies and Preference assessments. However, not all studies demonstrated the provision of ES within bundles. To identify such studies, a further literature review was performed. Since Raudsepp-Hearne et al. (2010) first developed this framework, the search for peer-reviewed papers spanned from 2010 to December 15th 2019, including the mapping studies identified by Saidi & Spray (2018). The search was performed on the Scopus database using the keywords "ecosystem services" and "bundles" and "mapping or map" and "cluster". For studies to be considered as ES studies identifying ES bundles, their bundling framework has to follow four general steps: (1) mapping and quantification of ES, (2) analyzing ES relationships through statistical means [correlation, PCA etc], (3) identification of bundles, and (4) quantifying ES within each bundle. The results produced 67 studies that analyzed ES relationships and identified ES bundles (Table 2.4). The objective of most studies was to provide information about ES patterns for improving landscape or ecosystem-specific management and ensure sustainable resource consumption. Therefore, the exploration of ES interactions and bundles as indicators of the existence of socio-ecological systems is of primary importance.

Table 2.4: Extended full list of ES bundles approaches/studies that have been published during the period 2010 – December 15th 2019. Adapted from Saidi & Spray (2018).

YEAR OF PUBLICATION	REFERENCES	MAIN OBJECTIVE	MULTI-TEMPORAL	COUNTRY/REGION
2010	Raudsepp-Hearne et al. (2010)	Informing landscape planning and management	×	Canada
2012	Maes et al. (2012b)	Assessing the impact of land dynamics on ES	×	Europe
2012	Willaarts et al. (2012)	improve land management through achieving "win–win" solutions	×	South-west Spain
2013	García-Nieto et al. (2013)	Exploring patterns among multiple ES	×	South-east Spain
2013	Plieninger et al. (2013)	Exploring patterns between ES and socio-environmental factors.	×	Eastern Germany
2013	Qiu & Turner (2013)	Exploring patterns among multiple ES	×	USA
2014	Hanspach et al. (2014)	Assessing the impact of land dynamics on ES	Multi-scenario	Romania
2014	Turner et al. (2014)	Informing landscape planning and management	×	Denmark
2015	Crouzat et al. (2015)	Exploring patterns among multiple ES	×	French Alps
2015	Derkzen et al. (2015)	Informing urban planning and management	×	The Netherlands
2015	García-Llorente et al. (2015)	Land-use management	×	South-east Spain
2015	Hamann et al. (2015)	Informing landscape planning and management	×	South Africa
2015	Queiroz et al. (2015)	Informing landscape planning and management	×	South-central Sweden
2015	Renard et al. (2015)	Assessing the impact of land dynamics on ES	✓	Canada
2015	Yang et al. (2015)	Informing urban planning and management	×	China
2016	Depellegrin et al. (2016)	Exploring patterns among multiple ES	×	Lithuania
2016	Lamy et al. (2016)	Assessing the impact of land dynamics on ES	×	Canada
2016	Raudsepp-Hearne & Peterson (2016)	Addressing challenges in ES bundling	×	Canada
2016	Schulze et al. (2016)	Assessing the impact of land-use decisions on ES	Multi-scenario	Germany
2016	Yao et al. (2016)	Informing landscape planning and management	×	North-eastern China
2017	Baró et al. (2017)	Informing landscape planning and management	×	Spain
2017	Dittrich et al. (2017a)	Exploring patterns between ES and socio-environmental factors.	×	Germany
2017	Dittrich et al. (2017b)	Informing landscape planning and management	×	Germany

Table 2.4: (Continued).

YEAR OF PUBLICATION	REFERENCES	MAIN OBJECTIVE	MULTI-TEMPORAL	COUNTRY/REGION
2017	Egarter Vigl et al. (2017b)	Exploring patterns among multiple ES	✗	European Alps
2017	Li et al. (2017a)	Guide targeted land use policy-making	✓	China
2017	Mouchet et al. (2017b)	Assessing the impact of land dynamics on ES	✗	Europe
2017	Ryschawy et al. (2017)	Informing landscape planning and management	✗	France
2017	Roussel et al. (2017)	Informing urban planning and management	✗	France
2017	van der Zanden et al. (2017)	Assessing the impact of land dynamics on ES	✗	Europe
2018	Balzan et al. (2018a)	Informing landscape planning and management	✗	Malta
2018	Chawanji et al. (2018)	Exploring patterns among multiple ES	✗	Zimbabwe
2018	(Dou et al., 2018)	Addressing challenges in ES bundling	✗	China
2018	Fan et al. (2018)	Informing land use planning and management	✓	Eastern China
2018	Frei et al. (2018)	Inform agricultural planning and management	✗	Canada
2018	Frueh-Mueller et al. (2018)	Informing landscape planning and management	✗	Germany
2018	Kong et al. (2018)	Informing landscape planning and management	✗	China
2018	Lin et al. (2018)	Informing landscape planning and management	✗	China
2018	Lorilla et al. (2018)	Informing landscape planning and management	✓	Greece
2018	Lyu et al. (2018)	Informing urban planning and management	✓	China
2018	Marsboom et al. (2018)	Informing landscape planning and management	✗	Belgium
2018	Oteros-Rozas et al. (2018)	Exploring patterns between ES and socio-environmental factors.	✗	Europe
2018	Peña et al. (2018)	Informing landscape planning and management	✗	Northern Spain
2018	Torralba et al. (2018)	Inform agricultural planning and management	✗	Areas of European countries
2018	Zhao et al. (2018)	Informing river delta planning and management	✗	China
2019	Bengtsson et al. (2019)	Informing landscape planning and management	✗	Europe

Table 2.4: (Continued).

YEAR OF PUBLICATION	REFERENCES	MAIN OBJECTIVE	MULTI-TEMPORAL	COUNTRY/REGION
2019	Benra et al. (2019)	Informing landscape planning and management	✗	Southern Chile
2019	Dumont et al. (2019)	Exploring associations among goods, impacts and ecosystem services	✗	Europe
2019	Gao et al. (2019)	Guide sustainable urban agglomeration planning and development.	✗	China
2019	Haberman & Bennett (2019)	Adressing possible linkages between ES and biophysical and socio-economic factors.	✗	Global
2019	Inostroza (2019)	Informing landscape planning and management	✗	Region between Poland and the Czech Republic
2019	Jaligot et al. (2019a)	Informing land management	✓	Switzerland
2019	Jaligot et al. (2019b)	Exploring spatio-temporal patterns of ES	✓	Switzerland
2019	Khosravi Mashizi et al. (2019)	Informing rangeland planning and management	✗	South-east Iran
2019	Madrigal-Martínez & Miralles i García (2019)	Inform land management actions and policy decisions	✓	Peru
2019	Meyer et al. (2019)	Explore the linkages between forest ES use and demand	✗	German Federal State of Bavaria
2019	Li et al. (2019)	Informing landscape planning and management	✓	North China
2019	Liu et al. (2019b)	Assessing the impact of land dynamics on ES	✓	North China
2019	Liu et al. (2019a)	Informing landscape planning and management	✗	Three counties in China
2019	Lyu et al. (2019a)	Informing ES management	✗	China
2019	Lyu et al. (2019b)	Informing urban planning and management	✓	China
2019	Plieninger et al. (2019)	Exploring patterns between ES and socio-cultural factors.	✗	Europe
2019	Quintas-Soriano et al. (2019)	Exploring patterns among multiple ES	✗	Spain
2019	Schirpke et al. (2019a)	Exploring patterns among multiple ES	✗	European Alps
2019	Vannier et al. (2019)	Informing landscape planning and management	✗	France
2019	Yang et al. (2019a)	Informing urban and agricultural planning and management	✗	North-eastern China
2019	Yang et al. (2019b)	Assessing the impact of land dynamics on ES	✓	North-eastern China
2019	Zoderer et al. (2019)	Informing landscape planning and management	✗	Northern Italy

Raudsepp-Hearne et al. (2010), who were the ones that conceptualized the ES bundling framework, recognized that the interactions among multiple ES can be strongly shaped by social and ecological forces. Therefore, assessing ES bundles should be applied where decision process, regarding the management of ESs, are likely to be made. Despite there being a wealth of literature about mapping and quantifying ES bundles, a recent literature review (Balzan et al., 2018b) showed that few studies have investigated interactions among services of island ecosystems, which is important to the identification of management practices optimizing or negatively affecting the potential of island landscapes to provide ESs. Especially for Mediterranean islands, which constitute a biodiversity hotspot with high natural and cultural values (Kefalas et al., 2018; Lorilla et al., 2018; Lorilla et al., 2019), the identification of trade-off situations is of primary importance. On the perceptions of coastal populations in a Mediterranean landscape, provisioning ES and non-provisioning ES (regulating and cultural) are seen as equally important; however, a strong preference for cultural ES can be observed (Soy-Massoni et al, 2016).

2.5.1 Changes in ecosystem service bundles through time

However, the benefits provided from ESs are not static, or fixed, rather they depend on the dynamic nature of ecosystem structures and functions (Fisher et al., 2009). To avoid future impacts on the provision of benefits to society and to effectively manage ES provision, it is inevitable to identify possible conflicts among ESs across space and time (Rau et al., 2018). For example, Tomscha & Gergel (2016) demonstrated the importance of monitoring long-term interactions among ESs to manage heterogeneous landscapes. Similarly, Sutherland et al. (2016) showed the utility of monitoring the long-term recovery of ES from timber harvest to maintain multifunctional forests. On the other hand, Koch et al. (2009) showed that a lack of information on the temporal and spatial variability of coastal characteristics generates additional management problems when protecting coastal areas.

From the studies identified in Table 2.4, only twelve have assessed ES relationships and bundles through a temporal scale, with nine of them conducted in China, Canada and Switzerland. Renard et al. (2015) first used the ES bundle approach to explore the importance of historical dynamics (35-year dataset) in a mixed-use landscape to identify processes and drivers behind the changing relationships among ESs. In specific, their study demonstrated the limitations of assuming stationarity in ESs and their relationships, and emphasized the importance of taking into account both time and space in the assessment of multiple ESs. Following Renard et al. (2015), Jaligot et al. (2019b) observed different patterns of ES relationships through time and provided clear evidence of the dynamic nature of ESs. Whereas, Madrigal-Martínez & Miralles i García (2019) demonstrated that land transformation of large areas is not necessarily equivalent to high variations in the supply of ESs. Despite the importance of ES provision in the Mediterranean basin, along with the historical dynamics of Mediterranean ecosystems (Metzger et al., 2006), studies on the historical assessment of ESs are lacking. Therefore, more explicit temporal analyses of ESs can enable informed decisions in ecosystem management and prevent unintentional trade-offs (Rau et al., 2019).

2.6 Spatial congruence and mismatches between the supply and demand of ecosystem services

The imbalance between economic growth and the limited natural resources poses one of the most crucial challenges of our modern history (Syrbe & Grunewald, 2017). The main problem is that few ES resources are known to the wider public or sustainably used. When usage exceeds the capacity of ecosystems to provide services, the natural environment can be negatively affected, causing the depletion of ES supply and unfulfilled demand (Wolff et al., 2015). The ES concept, therefore, describes not only the ecosystem functions and processes but also identifies the existence of human impact on the environment. The latter case includes understanding the balance between the supply of and the demand for ESs as key towards elucidating how people and nature are linked. In addition, the inclusion of ES demand in ecosystem assessment is assumed to increase policy relevance and practical application of the ES concept in operational management (Wolff et al., 2015). Thus, the confrontation of ES supply and demand and their associations can sustainably improve ecosystem management through uncovering possible imbalances [or unsustainable use of resources] (Syrbe & Grunewald, 2017).

Several studies have attempted to integrate the supply and social demand in ES assessments. Schulp et al. (2014) quantified the supply and demand of agricultural pollination services in Europe, showing that the demand area was larger than the supply area. In southern Spain, Castro et al. (2014) investigated both supply and social demand by spatially analyzing ES trade-offs from biophysical, socio-cultural, and economic perspectives. Wei et al. (2018) used a biophysical model and conducted a questionnaire to link ES supply, social demand, and human well-being. To identify spatial mismatches in ESs, Goldenberg et al. (2017) showed that the urban regions present excessively high ES demand, while forested areas are characterized by excess ES supply.

In all cases, the researchers accounted for both the supply and demand of ESs to identify potential mismatches and to provide insights for enhancing human well-being.

After a thorough literature search in the Scopus database, a final list of studies that identified spatial mismatches/imbalances between the supply and demand of ESs was created. (Table 2.5). The search was performed using two keyword combinations: (1) [*ecosystem AND servic* AND suppl* AND demand* AND (relationship* OR interaction* OR association*) AND (spatial* OR map* OR overlap*)*], and (2) [*ecosystem AND servic* AND suppl* AND demand* AND (hotspot* OR hot-spot* OR spatial*) AND (match* OR mismatch* OR congruenc* OR connect*)*]. The first case produced 92 results, and the second 78 results. From these studies, 36 cases were identified as relevant assessments.

Table 2.5: List of studies on identifying spatial mismatches between ES supply and demand. Source: own elaboration.

APPROACH	REFERENCES
ES MATRIX	Burkhard et al. (2012)
	Chen et al. (2020b)
	Egarter Vigl et al. (2017a)
	Nedkov & Burkhard (2012)
	Sun et al. (2020)
EQUATION-BASED	Boithias et al. (2014)
	Chen et al. (2019a)
	Chen et al. (2019b)
	Cui et al. (2019)
	Guan et al. (2020)
	Li et al. (2016b)
	Maragno et al. (2018)
	Meisch et al., (2019)
	Orta Ortiz & Geneletti (2018)
	Sun et al. (2019)
	Tratalos et al. (2016)
	Zhang et al. (2017)

APPROACH	REFERENCES
HOTSPOTS	Bagstad et al. (2016)
	Lorilla et al. (2019)
	Schirpke et al. (2018)
	Schirpke et al. (2019b)
	Tardieu & Tuffery (2019)
SPATIAL OVERLAP	Zhao et al. (2019)
	Koh et al. (2016)
	Ma et al. (2019)
	O'Higgins et al. (2019)
	Schulp et al. (2014)
	Shen et al. (2019)
	Stürck et al. (2014)
	Stürck et al. (2015)
	Wang et al. (2019)
OTHER	Beichler (2015)
	Baró et al. (2017)
	García-Llorente et al. (2015)
	Hatziiordanou et al. (2019)
	Quintas-Soriano et al. (2019)

Contrary to the identification of ES bundles, the selected studies uncovered spatially explicit similarities or mismatches. That is because the identification of spatial patterns, especially mismatches between ES supply and demand, is critical when ES assessments are translated into land-use or management decisions (Roces-Díaz et al., 2018). The main approaches for integrating both ES supply and demand, and for identifying their spatial imbalance were the ES matrix approach, hotspot analysis, equation/index-based, and overlap analysis. These approaches refer to the way with which supply and demand were connected and not the indicators used for quantifying an ES itself, which has been previously covered in section 2.2.

2.6.1 ES matrix approach

On to the ES matrix approach, Burkhard et al. (2012) proposed a land cover- and expert-based ES assessment to identify imbalances between the supply and demand of ESs. Following the same concept, various researchers applied the ES matrix to measure the balance between supply and demand in Bulgaria (Nedkov & Burkhard, 2012), Italy (Egarter Vigl et al., 2017a), China (Chen et al., 2020b) and the United States (Sun et al., 2020). By linking land cover information with data from monitoring, statistics, modeling or interviews, ES supply and demand can be transferred to different spatial and temporal scales (Burkhard et al., 2012), making the ES matrix framework a rather easy tool to begin an ES assessment quickly and efficiently. However, the matrix model entails risks for scientific credibility and legitimacy with regard to measures of confidence, traceability, consistency, reliability and validity (Gorn et al., 2018; Jacobs et al., 2015).

2.6.2 Equation-based approaches

To test whether the connection of supply and demand can portray the actual use of an ES, Boithias et al. (2014) compared a non-monetary supply-demand (S:D) ratio of water provision to its market price (monetary valuation). They found that the S:D ratio provided similar values and can be therefore used as a spatially explicit metric to evaluate the water provisioning. In the case of cultural ESs, Tratalos et al. (2016) also used an S:D ratio as an index for the relationship between supply and demand for recreational country parks. In an attempt to develop an indicator that may easily be transferable and comparable across different regions, Li et al. (2016b) formulated the supply-demand ratio (Equation 2.1). The supply-demand ratio indicator aimed at reflecting the relationship between the actual ES supply and human demand in space, which may indicate a deficit or a surplus:

$$\boldsymbol{supply - demand\ ratio} = \frac{supply_{actual} - demand_{human}}{(supply_{max} + demand_{max})/2} \begin{Bmatrix} > 0, surplus \\ = 0, balance \\ < 0, deficit \end{Bmatrix} \quad [2.1]$$

where $supply_{max}$ and $demand_{max}$ indicate the maximum value of actual ES supply and human demand, respectively, in a given area. A value greater than 0 indicates ES surplus, a value lower than 0 indicates a deficit and a value of 0 indicates a balanced state.

To suggest strategies to minimize the mismatch between ES supply and demand, Chen et al. (2019a) and Chen et al. (2019b) adapted the same indicator, referred to as the Ecological Supply-Demand Ratio or the ES Supply-Demand Ratio (also mentioned as ESDR). Specifically, the two studies aimed to reveal the temporal trend of ES for targeted, sustainable management and policy. In addition to the estimation of ESDR, Chen et al. (2019b) used a comprehensive supply-demand ratio (CESDR) [Equation 2.2], also employed by Chen et al. (2019a), to determine the status of ESs at the integral level, calculated as the arithmetic mean of ESDR:

$$\boldsymbol{CESDR} = \frac{1}{n}\sum_{i=1}^{n} ESDR_i \quad [2.2]$$

where n is number of estimated ESs and $ESDR_i$ is supply-demand ratio for each ES type i.

Apart from assessing ES mismatches at a temporal scale, Cui et al. (2019) tested the ESDR across different spatial scales (local, township and county level). Their findings suggested that the consideration of the overall supply of and demand for ES at a larger scale while implementing more precise management measures at a smaller scale can facilitate more effective management of ESs. Another equation-based approach that has been reported as an index of balance between ES supply and demand was given by Zhang et al. (2017), who evaluated the supply-and-demand balance for ESs [Equation 2.3] using the following formula:

$$\boldsymbol{IMES_B} = IMES_s - IMES_d \quad [2.3]$$

where $IMES_s$, $IMES_d$ and $IMES_B$ are the supply, demand and balance indices of multiple ESs, respectively; negative numbers indicate that the demand significantly exceeds the supply (undersupply), zero represents a neutral supply-and-demand balance, and positive values indicate that the supply significantly exceeds the demand (oversupply). A similar logic was applied to visualize spatial mismatches between freshwater provision and consumption in the Alpine Space by subtracting water use from water supply (Meisch et al., 2019).

All the above studies developed and applied an equation-based approach to assessing both spatial similarities and mismatches in a way where all states of the relationships between supply and demand would be visible. However, other researchers focused mainly on the unsatisfied demand for ESs. For example, Sun et al. (2019) measured the mismatch between the ES supply and demand for Grain provision and Carbon sequestration using the unsatisfied demand ratio (UDR). The UDR metric refers to the proportion of the demand not met by the supply to the total demand (Equation 2.4).

$$\boldsymbol{UDR} = \frac{D - S}{D} \quad [2.4]$$

where D and S represented the demand and supply of ESs, respectively.

Similarly, Orta Ortiz & Geneletti (2018) formulated a Recreation & Food Supply specific equation to estimate the unsatisfied demand mismatch expressed as the percentage of people that must travel over maximum distances to reach recreational sites, and for whom the production of local *organoponics* (a local Cuban product) has not met at least 45% of the food requirement. To implement mitigation actions, a Priority Index (PRI), referring to a ranking of the priority areas of intervention, was provided by Maragno et al. (2018), where the mismatch between ES demand and supply could orient urban planning.

Recently, a more precise methodology characterizing the relationship between ES supply and demand, with respect to the degree of match and coordination, was developed by Guan et al. (2020). Two ecological indexes, namely, the matching degree of supply and demand (MD-supply-demand) [Equation 2.5], and the coordination degree of supply and demand (CD-supply-demand) [Equation 2.6] were formulated as follows:

$$\boldsymbol{MD - supply - demand} = \frac{potential\ supply}{human\ demand} \begin{Bmatrix} < 1, unable\ to\ carry \\ = 1, balance \\ > 1, able\ to\ carry \end{Bmatrix} \quad [2.5]$$

$$\boldsymbol{CD - supply - demand} = \sqrt{\left[\frac{actual\ supply \times human\ demand}{\left(\frac{actual\ supply + human\ demand}{2} \right)^2} \right]} \quad [2.6]$$

The equation for MD-supply-demand followed the concept of the S:D ratio, with a three-tier classification (surplus, balance or deficit). Whereas, for CD-supply-demand, Guan et al. (2020)

divided the results of the degree of coordination into 12 grades. This particular ecological index characterizes the condition of the coordinated development of the supply and demand and could reveal the sustainability of regional ES.

$$\boldsymbol{CD-supply-demand} = \begin{cases} [0.00, 0.05)\ Complete\ inharmonious \\ [0.05, 0.10)\ Extreme\ inharmonious \\ [0.10, 0.20)\ Significant\ inharmonious \\ [0.20, 0.30)\ Moderate\ inharmonious \\ [0.30, 0.40)\ Slight\ inharmonious \\ [0.40, 0.50)\ Close\ to\ inharmonious \\ [0.50, 0.60)\ Basic\ Coordination \\ [0.60, 0.70)\ Bare\ Coordination \\ [0.70, 0.80)\ Rudimentary\ Coordination \\ [0.80, 0.90)\ Moderate\ Coordination \\ [0.90, 0.95)\ Good\ Coordination \\ [0.95, 1.00)\ Excellent\ Coordination \end{cases}$$

2.6.3 Hotspot analysis

Another method for identifying spatial mismatches between the supply and demand of ES is mapping hot and cold spots, allowing the visualization of priority areas (Li et al., 2017b). Schröter and Remme (2016) reviewed ES delineation methods through a literature search (Figure 2.5), demonstrating no clear link between distinct hot spot methods and specific ES policy questions/purposes. Yet, Bagstad et al. (2016; 2017) successfully used the Getis-Ord Gi* statistic (Getis & Ord, 1992) [Equation 2.7] to match both ES supply and social preference value when assessing synergies, trade-offs, and conflicts.

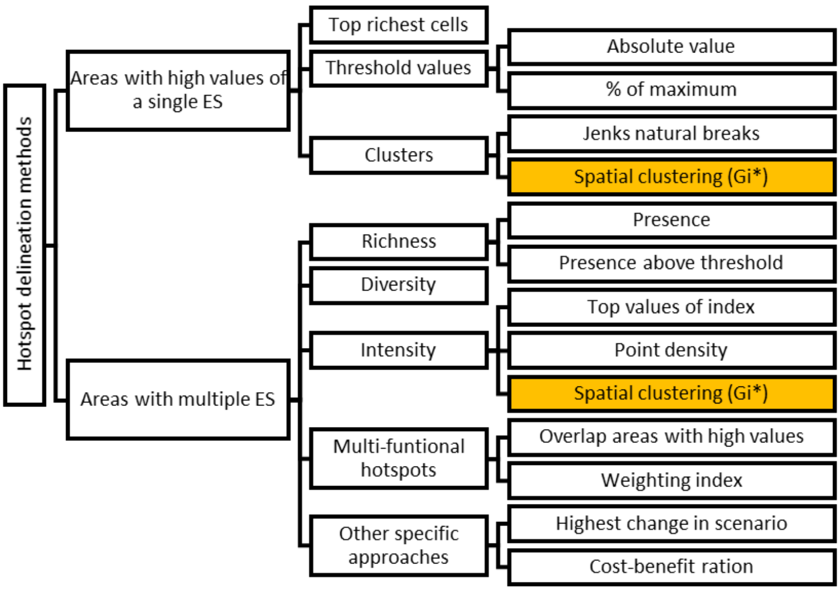

Figure 2.5: Classification of hotspot delineation methods. Adapted from Schröter & Remme (2016).

It is appropriate to use this statistical measure with feature type data, such as polygons and points (Schröter & Remme, 2016); however, it cannot be used in raster type variables. The Getis-Ord Gi* statistic, forms as follows (Roces-Díaz et al., 2018):

$$\boldsymbol{G_i^*} = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \left[\frac{\sum_{j=1}^{n} x_j}{n}\right] \sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} wi,j\right)^2}{n-1}}} \quad [2.7]$$

where n is the number of spatial features; $w_{i,j}$ is the distance between features i and j; x_j is the value of each ES; and S is calculated as:

$$\boldsymbol{S} = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - \left[\frac{\sum_{j=1}^{n} x_j}{n}\right]^2} \quad [2.8]$$

This method generates larger clustered areas that are connected throughout the landscape, and is preferable, as smaller areas could lose a considerable part of their value if neighboring areas are not conserved (Schröter & Remme, 2016). In Tardieu & Tuffery (2019), hotspot analysis (using the Getis-Ord Gi*) facilitated the characterization of a National Park in Italy into clusters based on a combined attractiveness index (CAI) for recreation estimated by supply and demand factors. Most importantly, the relevance of their work has been proven by the practical use of results in the design of policies in the park, including the special protection areas designed for an endangered bird species. Hotspot analysis has also appeared in studies as a complementary method to identify supply-demand mismatches (Lorilla et al., 2019). For example, Schirpke et al. (2018; 2019b) employed the Getis-Ord Gi* statistic to identify hotspots of ESs, to which they further applied cluster analysis and overlap analysis, respectively, to reveal spatial congruencies and mismatches.

2.6.4 Spatial overlap approaches

Similar to hotspots analysis but simpler, overlaid analysis has been used to delineate spatial congruence or mismatches of ES supply and demand at city (Zhao et al., 2019), country (Wang et al., 2019) and continental scale (Schulp et al., 2014; Stürck et al., 2015). Despite the simplicity of such a method, spatial overlap has also been used to identify the production and consumption of complex coastal ES (O'Higgins et al., 2019). Bivariate mapping, which could be considered as an overlaid analysis, is a cartographic technique used to display two variables on a map by combining two different sets of graphic symbols or colors. In the study of Shen et al. (2019), a color matrix was constructed to represent the interaction between the supply and demand for flood regulation. They particularly tried to improve the quantile method followed by Stürck et al., (2014) that, as Shen et al. (2019) stated, "*identified only the areas where both the demand and the supply of the Flood regulation were high but failed to consider the spatial match or mismatch*". Koh et al. (2016) also used bivariate mapping to compare the supply and demand for pollination services, represented by wild bee abundance and cultivated area, respectively. Similarly, in the case of ES changes, Ma et al. (2019) followed the general concept of the bivariate mapping technique to analyze the match or mismatch in supply and demand trends of water security for community settlements through looking at changes in supply to a settlement, and the quantity demanded by that settlement. Their findings revealed clusters that may appear to have adopted more sustainable management practices over time and areas where changes in ESs are likely to occur.

Other approaches for identifying ES mismatches consisted neighborhood analysis to explore interrelations between the supply and demand of cultural ESs (Beichler, 2015), and structural connectivity analysis to integrate EU Biodiversity Strategy demands into mapping and assessment of the habitat maintenance ES (Hatziiordanou et al., 2019). In addition, similar to the ES bundling framework, various researchers performed cluster analysis to spatially identify bundles of ES, including supply and demand indicators (Baró et al., 2017; García-Llorente et al., 2015; Quintas-Soriano et al., 2019).

2.7 Drivers of ecosystem services

The capacity of an ecosystem to supply ESs depends on the state of its structure, processes and functions determined by the interactions with socio-economic systems. In the last few decades, the impact of human activities on ecosystems have increased rapidly. While the majority of these can be considered beneficial to human well-being on the short-term, on the long-term there will be adverse effects on ecosystems and their services, and thus on humans themselves (MEA, 2003). Therefore, the understanding of factors and drivers determining ESs requires the study and exploration of the underlying ecosystem processes, because changes in ecosystems is directly affecting the changes in ESs.

The MEA (2005) analyzed drivers with respect to their past and current impact on different ecosystems and the biodiversity they support (Figure 2.6). Reduction of biodiversity implies a reduction in ecological resilience, which increases the risk that local communities will lose ESs (Mäler & Vincent, 2005). For Mediterranean ecosystems and islands in general, invasive species, habitat change and overexploitation of natural resources have always affected, and continue to have an increasing impact on biodiversity. In the past, such sensitive ecosystems were low affected by climate change and pollution, whereas, current trends present these drivers to have rapidly increased their impact on biodiversity, and therefore, on ESs.

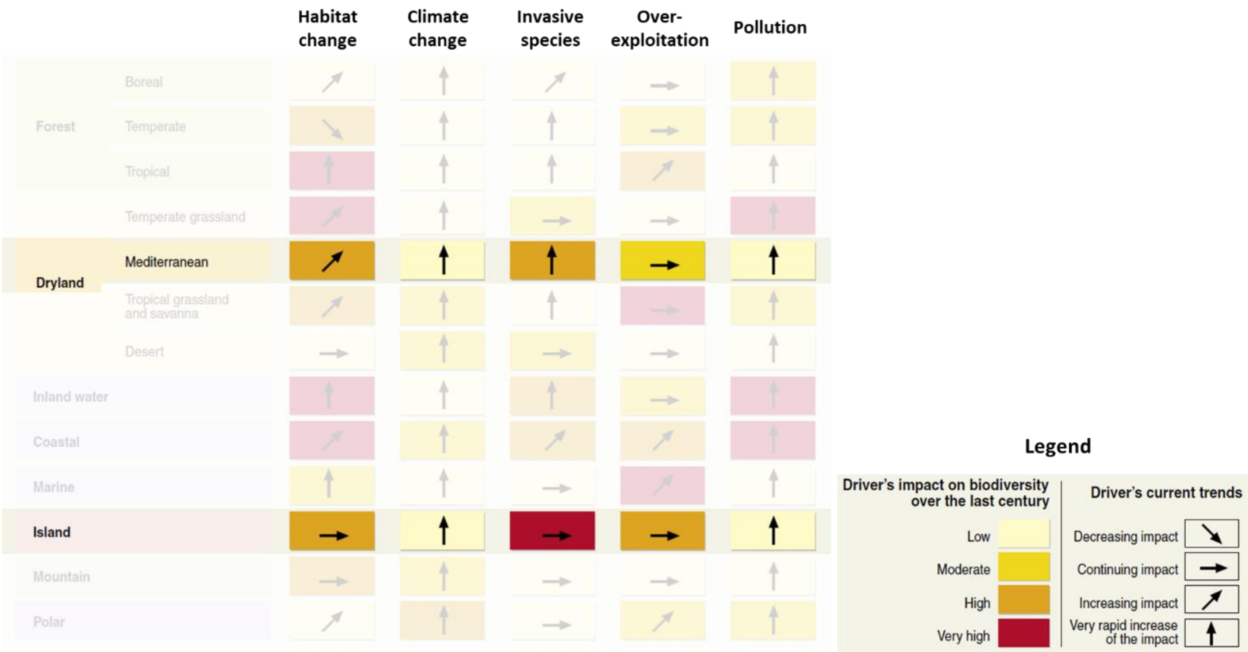

Figure 2.6: Drivers of change and their impact on ecosystems and biodiversity. Adapted and modified from the MEA (2005).

2.7.1 Typologies of drivers

Different meanings have been reported to conceptualize drivers of change (Geist & Lambin, 2002) referred to proximate causes and underlying driving forces. *Proximate causes* are generally human activities or immediate actions at the local level that have direct impact on land cover and land use; but to explain the reason for the proximate causes, *underlying driving forces* have to be assessed (Ostwald et al., 2009). This conceptual framework has often been used for land use/cover change studies on different regions (Geist, 2002; Kefalas et al., 2019; Parjiono et al., 2013; Qasim et al., 2013; Quezada et al., 2014; Yu et al., 2018). To clearly identify information about all elements of the causal chain that links human activities to their ultimate environmental impacts and the societal responses to these impacts, the European Environment Agency (1999) developed the DPSIR framework. According to this framework, which has been widely adopted (Bradley & Yee, 2015), the chain of causal links starts with *Driving forces* through *Pressures* to

States and *Impacts* on ecosystems, human health and functions, eventually leading to *political Responses*. Drivers of change fall into the driving forces and pressures elements, including, economic sectors, human activities, emissions and waste.

The Millennium Ecosystem Assessment that brought ESs back to the spotlight defined drivers as natural or human-induced factors that directly or indirectly cause a change in an ecosystem and therefore to its services (MEA, 2005). The difference between indirect and direct drivers is similar to that of the pressures and driving forces within the DPSIR framework, respectively, where the latter directly influence ecosystem processes, while the former operate more diffusely, often by altering one of the more direct drivers. The key indirect driving forces of ecosystem change are population, income, technological development, and changes in human behavior, whereas direct drivers are mainly physical, biological, or chemical processes. Despite the diverse meanings and typologies of drivers of change, we can agree that the analysis of drivers is a prerequisite to guide policies that otherwise would alter ecosystem conditions and, therefore, risk ecological integrity and the people depended on its maintenance.

Drivers of change, particularly anthropogenic factors, operate at various scales, possibly different from the ones carried out by ecosystem processes or specific organisms (Marty et al., 2014). Specifically, climate change may operate on a global or regional spatial scale, socio-cultural change typically occurs on a time scale of decades, and economic changes tend to occur more rapidly (MEA, 2005). Furthermore, policy and management interventions may operate as actors at multiple scales, such as national or municipal district scale, which do not always fit the scale of the above anthropogenic factors, socio-cultural or ecosystem processes (Marty et al., 2014). Additionally, changes in ESs are almost always caused by multiple, interacting drivers that work over time. For example, population and income growth interact with technological advances that could lead to climate change (Nelson et al., 2005).

2.7.2 Revealing drivers of ecosystem services

By now it is clear that the state of ecosystems is not only influenced by their ability to provide services but also depends on the human desire for such services. A key challenge ecologists and ecosystem managers face is understanding what may drive unexpected shifts (Filbee-Dexter et al., 2018). In parallel, many researchers have demonstrated that land use changes can alter patterns, functions and processes of ecosystems and landscapes, eventually leading to alterations in the status of ESs.

Numerical statistical methods can be used to identify drivers (socio-economic, environmental or both) that affect the distribution of ESs and their bundles. Such methods include distance approach (e.g. Mantel test), analysis of variance, regression-based models, machine learning methods, time series methods and canonical analysis (Mouchet et al., 2014). On applying a suite of standard statistical methods (K-means cluster analysis, correlation coefficients and Redundancy Analysis - RDA), the findings of Liu et al. (2019b) suggest that precipitation and terrain ruggedness were the most important factors in determining regulating ESs, while for provisioning and cultural ESs, population density was the most important influencing factor. Also with redundancy analysis (Jaligot et al., 2019a) revealed that the main influencing factors of cultural ESs was population density, whereas slope, altitude, protected areas and agricultural land contributed to the spatial and temporal patterns of regulating ESs.

To guide experts into identifying the key characteristics of social-ecological systems, Balzan et al. (2019) followed the DPSIR framework, where demography and economic development, land use management changes, urbanization and maritime traffic are reported to have strongly affected biodiversity in the Mediterranean areas. Also, to identify the management drivers behind the provision of carbon forest hotspots, Timilsina et al. (2013) developed a framework based on spatial statistics using biophysical and disturbance factors. Their generalized linear mixed model showed no significant links between the disturbance variables (fire and windstorm), whereas biophysical drivers, such as forest vegetation type and wood volume production increased the probability of an area being located in a carbon hotspot. Similarly, biophysical indicators representing age of forest stand, rainfall and species richness supported high amounts of aboveground biomass in a managed forest landscape (Souza et al., 2019).

Models can help us understand ecosystem complexity, including for example, how the supply or the demand for ESs are related to external driving forces causing possible ecosystem changes. Otherwise, management or policy measures that may miss this complexity can lead to adverse effects to multiple ESs. In the Norrström drainage basin (southcentral Sweden), Meacham et al. (2016) evaluated how well alternative socio-ecological models of human impact on ecosystems (namely, land use, ecological modernization, ecological footprint, and location theory) explained patterns of multiple ESs. Using a combination of linear models and Random Forest, they identified land use as an important driver of provisioning ES, while socioeconomic development and landscape’s isolation best predicted cultural ESs. Qiu & Turner (2013) used a backward logistic regression model to identify potential explanatory variables of ESs, where the amount of adjacent wetlands, depth to water table, and soil silt were positively associated with the occurrence of “win–win” areas. To map socio–ecological systems based on the direct use of ESs by households, Hamann et al. (2015) used a multinomial logit model to detect the most important social and ecological predictors. The distribution of such socio–ecological systems was mainly determined by social factors, such as household income, gender of the household head, and land tenure, and only partly determined by the supply of natural resources. Using a new statistical method (GeoDetector) [Wang & Xu, 2017] for detecting spatial stratified heterogeneity and revealing the driving factors behind it, Chen et al. (2020a) identified socio-economic characteristics, altitude and temperature as important indicators affecting ES bundles.

Land use types and changes, impacted by both economy and population growth, has greatly affected the natural capital of ecosystems along with their ESs, regardless of the area being studied (Zheng et al., 2019). It is not therefore surprising that land use is also considered a key factor in simulating future supply of ESs (Carpenter et al., 2015; Kim et al., 2019; Liu et al., 2018). Also, climate change has shown strong influence to the management recommendations of local authorities and disturbances (Seidl et al., 2019). Nevertheless, changes in the status of ecosystems, which are driven by land demand to satisfy human well-being, have resulted in declines of ESs. Especially when these alterations are strongly connected with urbanization, the socio-economic profile of residents and agricultural activities, ecosystem resilience and human well-being are at stake (Eigenbrod et al., 2011; Rukundo et al., 2018; Santos-Martín et al., 2013; Xu et al., 2014). However, while land use changes and anthropogenic factors have important effects on ESs, only few studies have explored the drivers of ES supply and demand altogether (Sun et al., 2020). Furthermore, finding and describing positive and negative co-occurrences of ESs is only the first step towards understanding ES relationships. Therefore, as mentioned throughout this thesis, to be able to support management decisions, we need to develop a complete understanding of complex socio-ecological systems, which means identifying key drivers and underlying mechanisms that cause ES associations and produce ES bundles (Spake et al., 2017).

Recently, Sun et al. (2020) proposed an integrated methodology to offset ES imbalances by identifying optimal land use strategies. Their framework included the exploration of the impact of different drivers on ES, through ordination and regression modelling analysis, the results of which showed that the expansion of developed land led to decreased ES supply and increased ES demand. To explore the proximate causes of the mismatch of ESs Sun et al. (2019) used redundancy analysis and found that urbanization rate and the proportion of cultivated land had a significant influence on the unsatisfied demand for ESs. Besides classical statistical analyses and regression models, other methods that have increasingly been used for species distribution modeling should be referred when the relationships among variables are complex (Mouchet et al., 2014). Such methods are machine learning techniques, including, Tree-based Methods, Artificial Neural Networks, Support Vector Machines, Genetic Algorithm, Fuzzy Inference Systems, and Bayesian Methods (Thessen, 2016; Willcock et al., 2018). Using a machine learning technique (Random Forest) Schirpke et al. (2019a) attempted to explain the spatial distribution of both supply and demand ES bundles, and their associations, with multiple socio-ecological drivers estimated at the municipality level. Similar to the findings of various studies on ES determinants, land use types showed important contribution to the spatial distribution of supply bundles, while population and livestock explained bundles of ES demand.

2.8 Integrating ecosystem services in decision-making

The general scope of mapping and assessing ESs, and therefore of this thesis, is to determine implications for policy and decision-making and enhance environmental, spatial and landscape planning. Spatial and landscape planning are generally concerned with the spatial configuration and management of land systems but slightly differ in focus and disciplinary orientation (Burkhard & Maes, 2017, p. 305). Spatial planning is a decision-making process in which the coordination of practices and policies, possibly including zoning, may affect spatial arrangement (Mascarenhas et al., 2015). Whereas, landscape planning is a strong forward looking activity, concerned with developing landscaping amongst competing land uses, while protecting significant cultural and natural resources (Antrop, 2005; Council of Europe, 2000). Both spatial and landscape planning have clear and direct impact on the supply of multiple ESs (Rozas-Vásquez et al., 2019). An effective integration of ESs assessment in planning requires recognition of democratically legitimized environmental objectives, providing the means to assess anthropogenic pressures and impacts, and to identify specific locations where management measures are likely to be most beneficial to both humans and ecosystems (Rozas-Vásquez et al., 2018).

A clearly defined research question for the use of the extracted information is the basis of any ES study aiming to facilitate the decision-making process towards the sustainable management of natural resources. Daily et al. (2009) presented a framework for the role that ESs can play in decision-making (Figure 2.7). The main aim is understanding and valuing ESs to make better decisions, resulting in better actions related to the use of land, water, and other elements of natural capital. A decision occurs when management actions are implemented through their integration in policy and plans, and are typically operationalized as some form of regulation or incentive (Martinez-Harms et al., 2015). Such incentives should reflect the social values of ESs, which, Ideally, individuals, land managers, and government officials, i.e. the ones who make decisions that affect ecosystems, will pay the prices for either using or affecting the supplied ESs (Daily et al., 2009). In no way, price is the only thing that motivates the behavior and decision of people; however, it is a mean for passing on the information that nature is essential for sustaining and improving human well-being. The ES approach facilitates moving beyond the purely economic and monetary perspective to a multifunctional, socio-ecological, or human-nature view, making it a key aspect in convincing multiple actors for the humans' dependency on ecosystems. In this regard, human demand and decision- and policy-making are key drivers of land use change and thus, actors of change in ESs. In addition, the inclusion of a wider set of ESs reduces possible consequences of decision-making if a single sector was to be promoted (Tallis & Polasky, 2009).

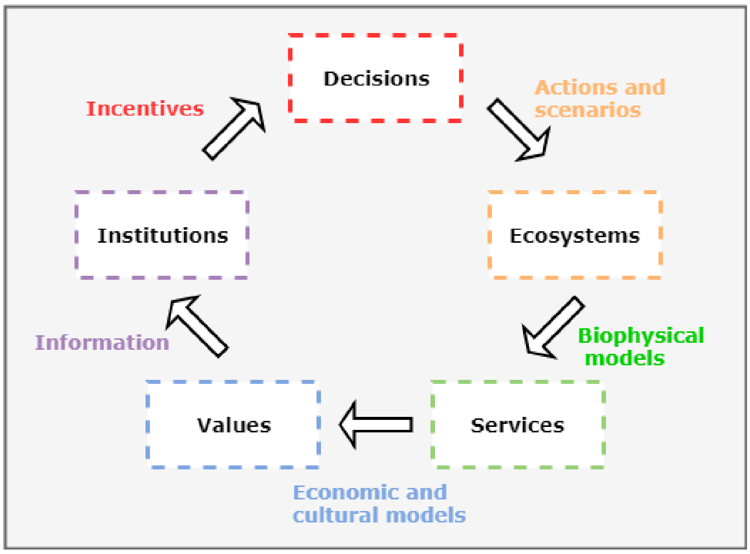

Figure 2.7: A suggested framework on how ESs can be integrated into decision-making. Adapted from Daily et al. (2009).

As such, the potential of the ES framework for supporting strategic decisions and the recognition of the urgent need to safeguard ESs has led to the establishment of new planning and policy documents, as well as the inclusion of ESs in existing agendas around the world (Egoh et al., 2012; Rozas-Vásquez et al., 2019). Global and European environmental policies aim to achieve the sustainable management of social-ecological systems to safeguard the long-term supply of ES

(Geijzendorffer et al., 2015). The ES concept and its implementation are identified as challenging topics on various scientific agendas (Figure 2.8), which aim to advance the understanding of how ES are provided to facilitate sustainable spatial planning and enhance the quality of life (Orta Ortiz & Geneletti, 2018). To, therefore, support an evidence-based policy and management responses, information on ESs is a crucial asset (Balzan et al., 2018a).

Figure 2.8: Global and European environmental agendas that have included the safeguard of ESs.

In 2015, the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States, developed a shared blueprint for peace and prosperity for people and the planet, now and into the future. Its core included 17 Sustainable Development Goals (SDGs), most of which rely on land systems because they support the link between human and nature. The Regional Assessment Report on Biodiversity and Ecosystem Services for Europe and Central Asia, published in 2018 and produced by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), provided a critical assessment of the full range of issues facing decision-makers, including the importance, status, trends and threats to biodiversity and ESs. The continuation of current trends in drivers (especially of land use and climate change) to the future will inhibit the achievement of various goals, including the SDGs (IPBES, 2018). By focusing on achieving a balanced supply of a diversity of ESs, it is more likely to help us succeed in search of achieving sustainable management of natural resources. Regional and transnational governance frameworks consequently need to connect areas of multiple ES supply to specific beneficiary groups and should account for the different levels and types of ES relationships (Schirpke et al., 2019a).

To sum it up, conducting an ES study first depends on the question being researched, which in the case of this thesis focuses on the implications of ESs in management decisions, which in turn may affect the Mediterranean ecosystems of the Ionian Islands. Depending on the prevalent sectors of the study area, the selection of ESs is of primary importance as the estimated ESs should interest the humans involved. Note that the indicators for the quantification of ESs, need to consider practicability and scientifically correctness and avoid oversimplification. Once ESs are quantified and mapped, a first attempt on defining priority areas can be made. In addition, exploring the temporal relationships among ESs offers insights on the possible future trends of ES provision and patterns of either synergistic or trade-off situations. However, as the capacity of an ecosystem to provide services depends on both biophysical characteristics and human desires for such services, the identification of an imbalance among supply and demand can point out vulnerable areas prone to overexploitation of ESs. Besides the visual or literature-based interpretation of the results, exploring underlying drivers of the spatial distribution of ES supply and demand can offer a complete understanding of ESs and their influencing factors. In this regard, possible policy implications can be suggested, with which land managers can act to mitigate further ecosystem degradation or maintain current policies to ensure a constant supply of ESs. The next chapters of this thesis are structured based on this general concept (Figure 2.9).

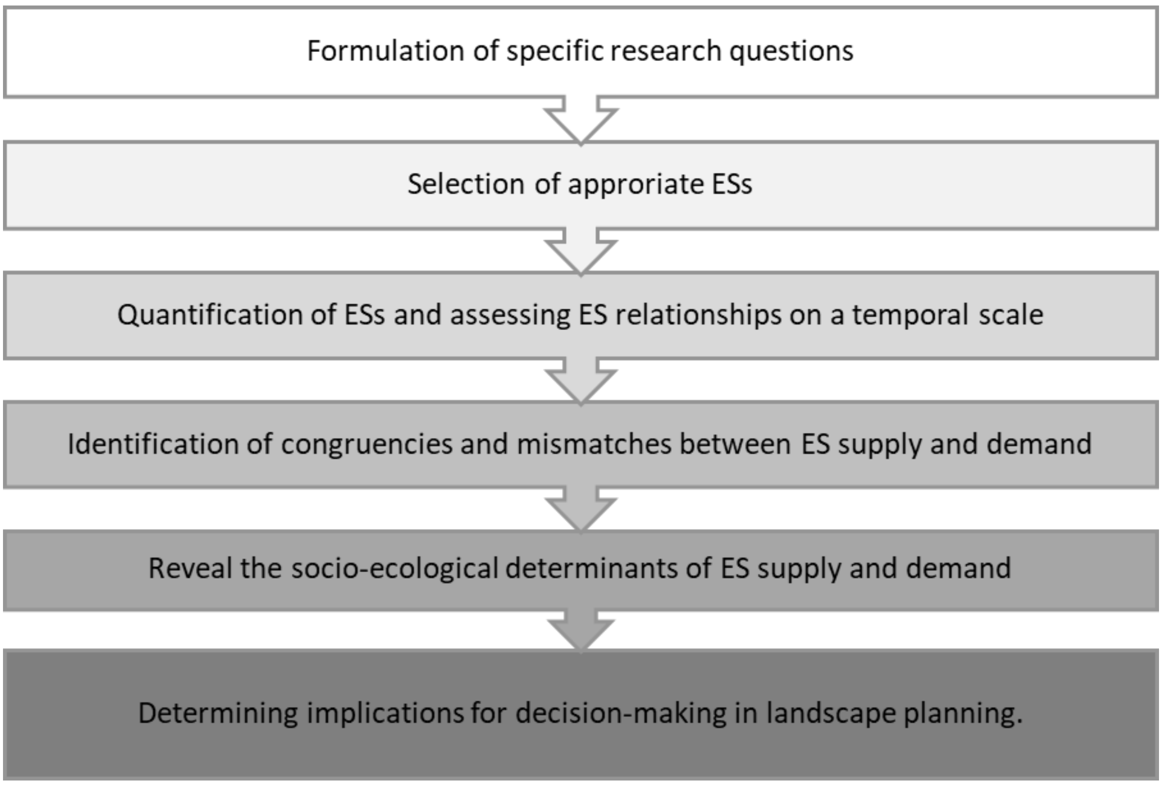

Figure 2.9: General structure of this PhD thesis in respect to the scope of ES assessments. Source: own elaboration.

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CHAPTER THREE

3 SPATIAL DYNAMICS AND INTERACTIONS AMONG THE SUPPLY OF ECOSYSTEM SERVICES[3]

"Because of the spatial peculiarity of ecosystem services, mapping their distributions and changes over time has the potential to aggregate complex information."

- Burkhard et al. (2012), Ecological Indicators

3.1 Contextual background

The sustainability of economic growth strongly depends on maintaining ecosystem services (ESs), a healthy environment, and cohesive societies (Carabine et al., 2015). Human well-being and sustainable development are dependent on improving the management of natural ecosystems, which secure their long-term sustainable use through conserving them (de Groot et al., 2010; MEA, 2003). Mapping and assessing ESs represent important approaches towards understanding the link between ecosystems and human society, which, in turn, facilitate decision-making and management based on sustainable development strategies (Crossman et al., 2013; Egoh et al., 2008; Tallis et al., 2008). A key challenge for ecosystem management is handling multiple ESs across landscapes (Termorshuizen & Opdam, 2009), as certain actions enhance the supply of some ES, while inhibiting others (Bennett et al., 2009). Addressing this challenge requires the identification of synergies and trade-offs that exist among ESs at different scales to promote sustainability in landscape management (Plieninger et al., 2013; Raudsepp-Hearne et al., 2010). However, ES interactions are not constant over time, resulting in temporal changes being overlooked in ES-based approaches, which might lead to the misrepresentation of their synergies, leading to future trade-offs (Renard et al., 2015; Tomscha & Gergel, 2016). In this context, this chapter focuses on assessing the spatial and temporal dynamics of ES supply and their interactions across the Ionian Islands to optimize future ES provision and to mitigate current trade-offs, thereby, sustaining well-functioning ecosystems.

[3] Parts of this chapter have been published in the form of a scientific article. Citation: Lorilla, R. S., Poirazidis, K., Kalogirou, S., Detsis, V., & Martinis, A. (2018). *Assessment of the spatial dynamics and interactions among multiple ecosystem services to promote effective policy making across Mediterranean island landscapes*. Sustainability, 10(9), 3285.

3.2 Methodology for mapping ES supply

3.2.1 Data sources

To map the supply of multiple ESs, a set of services was selected from the CICES system (Haines-Young & Potschin, 2018), based on the value of the estimated ESs in regional policy-making processes of the Ionian Islands, as well as data available throughout the entire study region. The list consisted of seven ESs and covered all ES sections/groups (Table 3.1). Specifically, three ES were selected for provisioning services, three for regulating and maintenance services, and one for cultural services. The mapping and quantification of ES supply was implemented for the 1985–2015 period, with a 10-year time step.

Table 3.1: List of the estimated ES and their relevant indicators/proxies. Source: adapted from Lorilla et al. (2018).

ES SECTION/GROUP	ES	CODE	INDICATOR/PROXY
PROVISIONING	Food Provision[1]	FP	Percentage of cultivated crops
	Materials from timber[1]	MT	Areas under forest and agroforest land
	Plant-based resources[2,3]	PR	Enhanced Vegetation Index (EVI)
REGULATING AND MAINTENANCE	Erosion protection[1,4,5,6]	EP	Soil Erosion Prevention (SEP)
	Climate regulation[1,7]	CR	Below and above ground carbon storage
	Maintenance of Nursery Populations and Habitats[1]	NS	Shannon Diversity Index (SHDI)
CULTURAL	Recreation[1,6,8,9]	RC	Recreation potential

[1] Land cover data with spatial resolution 30m based on Landsat Satellite images (Kefalas et al., 2018)

[2] Landsat 5 TM satellite images for the years 1985, 1995, and 2005 (https://earthexplorer.usgs.gov/)

[3] Landsat 8 OLI satellite image for the year 2015 (https://earthexplorer.usgs.gov/)

[4] European Soil Data Center—ESDAC (https://esdac.jrc.ec.europa.eu)

[5] Worldclim—global climate data (http://www.worldclim.org/)

[6] ASTER GDEM 30 m (https://search.earthdata.nasa.gov)

[7] Carbon Dioxide Information Analysis Center (DOE, 2016)

[8] European Ecological Network Natura 2000 (http://www.inspire.okxe.gr)

[9] Protected area management bodies (http://www.inspire.okxe.gr)

3.2.2 Provisioning services

Provisioning ES are all nutritional, material, and energetic outputs from living systems (Chapter 2). Food provision (FP) represents the production of cultivated plants or agricultural produce for human or animal consumption as food, fiber, or a source of energy (Raudsepp-Hearne et al., 2010). Materials from timber (MT) represent the products from trees harvested from natural forests and plantations (Maes et al., 2012b). Plant-based resources (PR) represent the capacity of ecosystems for energy production, which was estimated using the Enhanced Vegetation Index (EVI) from Landsat satellite images (Figure S1 in the Supplementary material). The EVI is used as an indicator of productivity and for vegetation monitoring due to its sensitivity to high biomass [Equation 3.1] (De Araujo Barbosa et al., 2015; Feng et al., 2010; Jiang et al., 2008).

$$\boldsymbol{EVI} = G \times \frac{NIR\text{-}R}{NIR + C_1 \times R - C_2 \times B + L} \quad [3.1]$$

where NIR, R, and B are atmospherically corrected, or partially atmosphere corrected, surface reflectance in near-infrared, red, and blue bands, respectively. L is the canopy background adjustment. G is a gain factor. C_1 and C_2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band.

3.2.3 Regulating & Maintenance services

Regulating and Maintenance ES include the ways in which ecosystems control or modify the biotic and abiotic parameters of the environment to improve human well-being (Chapter 2). Erosion prevention (EP) represents the capacity of ecosystems to prevent erosion, and is calculated using the soil erosion prevention framework (Equation 3.2) by Guerra et al. (2016):

$$\boldsymbol{E_s} = Y - \beta_e \begin{cases} Y = R \times LS \times K \\ \beta_e = Y \times a \end{cases} \quad [3.2]$$

where E_s represents the actual ecosystem service provision (tons of soil not eroded), Y represents the structural impact, β_e represents the mitigated impact (where $a = C$ and $E_S = 1 - a$), R represents the rainfall erosivity factor, LS represents the topographic factor, K represents the soil erodibility factors, and C represents the vegetation cover factor. All estimated factors are given at Figure S2 in the Supplementary material.

Climate regulation (CR) represents the carbon storage values (Cushman et al., 2006), which are assigned to each land cover category (Table 3.2) and are used as a proxy to estimate the capacity of vegetation to contribute towards mitigating climate change.

Table 3.2: Values of carbon stored in live vegetation per land cover. Source: Cushman et al. (2006).

LULC CLASS	MEAN VALUE (tn C/ha)	LULC CLASS	MEAN VALUE (tn C/ha)
Forest	*130*	High-Density Olive Orchards	*40*
Shrubland	*9*	Medium-Density Olive Orchards	*30*
Transitional Vegetation	*9*	Low-Density Olive Orchards	*8*
Meadow	*30*	Vineyards	*8*
Phrygana	*9*	Arable land	*8*
Sparse Phrygana	*9*	Mixed Cultures	*8*
Open Areas/Rocks	*0*	Other Cultures	*8*
Burnt	*40*	Permanent Cultures	*8*
Urban	*0*		

Maintenance of Nursery Population and Habitats (NS) represents the suitable habitats for plant and animal nurseries and reproduction (European Environment Agency, 2017; Liquete et al., 2016), which can be estimated with the landscape metric SHDI (Figure S3 in the Supplementary material). In specific, Maes et al. (2014) a series of indicators to measure ESs under the EU Biodiversity Strategy, to which they propose to quantify the NS service with proxies such as conservation investments, habitat or landscape protection, biodiversity value, ecological status or diversity of habitats. To estimate SHDI land cover data and the FRAGSTATS software were used. FRAGSTATS is a computer software program designed to compute a wide variety of landscape metrics for categorical map patterns (McGarigal et al., 2012).

3.2.4 Cultural services

Recreation (RC) represents the combination of recreation-related indicators that are used to estimate recreation potential. Nature attractiveness for outdoor recreation is mainly affected by naturalness (Casado-Arzuaga et al., 2014; Peña et al., 2015), relief differencing (de Vries et al., 2007; Norton et al., 2012), landscape diversity (Frank et al., 2013; Ridding et al., 2018), and the existence of protected areas (Maes et al., 2012b; Paracchini et al., 2014). Specifically, naturalness is calculated using the naturalness evaluation index - NEI [Equation 3.3] (Baiamonte et al., 2009; 2015), in which the land cover data are reclassified into four categories (high natural systems, semi-natural systems, agricultural systems, and artificial systems).

$$\boldsymbol{NEI} = \frac{C_1 + 2 \times C_2 + 3 \times C_3}{3 \times (C_0 + C_1 + C_2 + C_3)} \quad [3.3]$$

where C_0 is the area covered by artificial systems, C_1 is the area covered by agricultural systems, C_2 is the area covered by semi-natural systems, and C_3 is the area covered by high naturalness systems. NEI ranges from 0 (where the landscape reaches a maximum artificial status) to 1 (where the landscape reaches the highest naturalness condition).

Relief differencing was calculated using the geodiversity index (diversity of geomorphological features) proposed by Benito-Calvo et al. (2009). First, 10 different geomorphological features were calculated with an unsupervised classification (ISODATA) based on multi-layer surface variables (elevation, slope, curvature, and roughness) of an ASTER (Advanced Space-borne Thermal Emission and Reflection radiometer) Global Digital Elevation Model with spatial resolution of 30 m. The ISODATA classification algorithm refers to an iterative self-organizing data analysis technique and was used to cluster the data elements into different classes (Dhodhi et al., 1999). Second, similar to the quantification of NS, geomorphological features were used to estimate SHDI with FRAGSTATS for measuring the geodiversity index.

The four indicators of Naturalness, Geodiversity, Landscape diversity and Presence of Protected Areas were normalized and assimilated to estimate the recreation supply (Figures S4 and S5 in the Supplementary material). The importance of each indicator was specified using the Analytical Hierarchy Process - AHP (Saaty, 2001), to estimate specific weights (Table 3.3). AHP is particularly useful as a decision tool for environmental management (Ludwig & Iannuzzi, 2006).

Table 3.3: Scale of relative importance suggested by Saaty (2001). Source: Zhang et al. (2013).

INTENSITY OF IMPORTANCE	DEFINITION	DESCRIPTION
1	Equal importance	Two factors contribute equally to objective
3	Weak importance of one over another	Experience and judgment slightly favor one factor over another
5	Essential or strong importance	Experience and judgment strongly favor one factor over another
7	Demonstrated importance	A factor is strongly favored and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one factor over another is the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
	1/9 1/8 1/7 1/6 1/5 1/4 1/3 1/2 1 2 3 4 5 6 7 8 9 ← Less Important More Important →	

However, when many pairwise comparisons are performed, some inconsistencies may typically arise. The AHP incorporates an effective technique for checking the consistency (CI) of the evaluations made by the decision maker when building each of the pairwise comparison matrices involved in the process (Zhang et al., 2013). A perfectly consistent decision maker should always obtain $CI = 0$, but small values of inconsistency may be tolerated. In particular, if

$$\frac{CI}{RI} < 0.1 \qquad [3.4]$$

the inconsistencies are tolerable, and a reliable result may be expected from the AHP. RI is the Random Index, i.e. the consistency index when the entries in the pairwise comparisons are completely random.

The AHP produced the importance of each factor for recreation (Table 3.4), where naturalness had the highest weight (0.6273), followed by geodiversity (0.2033), landscape diversity (0.1084), and the presence of protected areas (0.0610).

Table 3.4: Pairwise comparisons among the four factors of recreation supply. Source: own elaboration.

	NATURALNESS	GEODIVERSITY	LANDSCAPE DIVERSITY	PROTECTED AREAS
NATURALNESS	1.00	4.00	6.00	8.00
GEODIVERSITY	0.25	1.00	2.00	4.00
LANDSCAPE DIVERSITY	0.17	0.50	1.00	2.00
PROTECTED AREAS	0.13	0.25	0.50	1.00

CI=0.015325; CI/RI=0.02

3.3 Methodology for quantifying ES interactions and bundles

The values obtained from each ecosystem service were normalized to a scale between 0 and 1, based on the minimum and maximum values (Equation 3.5), where 0 indicates low ES supply and 1 high ES supply (Liquete et al., 2015).

$$ES' = \frac{ES - ES_{min}}{ES_{max} - ES_{min}} \qquad [3.5]$$

where ES' is the normalized ES, ES_{max} is the maximum value of ES, and ES_{min} is the minimum value of ES.

ESs were averaged to create the Total ES and the three ES sections/groups. Comparison of the supply of ES over time was displayed with boxplots. A boxplot is a compact distributional summary, displaying less detail than a histogram or kernel density, but also taking up less space (Tukey, 1977). Boxplots use robust summary statistics that are always located at actual data points, are quickly computable, and have no tuning parameters (Wickham & Stryjewski, 2011). They are particularly useful for comparing distributions across groups, as is the case of temporal ESs. In addition, one-way ANOVA (Analysis of variance) along with Games-Howell post hoc tests were used to identify any significant differences between the studied years. ANOVA is widely used in scientific research to test multiple, often complicated, hypotheses, by comparing the means of a response variable from several groups (Qian, 2017).

3.3.1 ES interaction analysis and bundles identification

To identify interactions among ES, an appropriate scale of analysis is required (Grêt-Regamey et al., 2014; Raudsepp-Hearne & Peterson, 2016; Xu et al., 2017). Specifically, three different spatial grids were tested (two grids consisting hexagons of 100ha and 200ha, and one grid consisting 267 municipal districts) to select an appropriate scale for assessing ES.

The small grid 100 ha represents a local scale. The mid-scale grid 200 ha integrates the influence of a diverse landscape in the supply of ES. The large administrative scale refers to land boundaries where planning and management decisions are likely to be made. A hexagonal grid was preferred over a rectangular grid, because it provided a better representation of spatial connectivity in a complex landscape (Schindler et al., 2008; Tammi et al., 2017). For each of the three grids, the average values were estimated using zonal statistics. These values were used to calculate Moran's I for measuring the spatial clustering and selecting the best scale. In specific, Moran's I was used to determine whether ES are misrepresented as the scale of observation becomes larger (Moran, 1950; Raudsepp-Hearne & Peterson, 2016). Moran's I (Equation 3.6) is one of the oldest and most common statistics used to examine spatial autocorrelation in spatial data (Kalogirou, 2003) and has been previously used in ES studies (Hamann et al., 2015; Kong et al., 2018; Qiu & Turner, 2013; Renard et al., 2015).

$$I = \frac{n}{S_0} \frac{\sum_i^n \sum_j^n w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_i^n (x_i - \bar{x})^2} \qquad [3.6]$$

where $S_0 = {}^1\!/_4\, i\ {}^1\!/_4\, j w_{ij}, w_{ij}$ is the spatial weights matrix, n is the number of samples indexed of samples indexed by i and j, and x is the variable of interest. Values range from −1 to 1, where positive values indicate a highly clustered pattern of similar values and negative indicates clustering of dissimilar values.

The framework for analyzing interactions among ES consisted of three main processes (Figure 3.1).

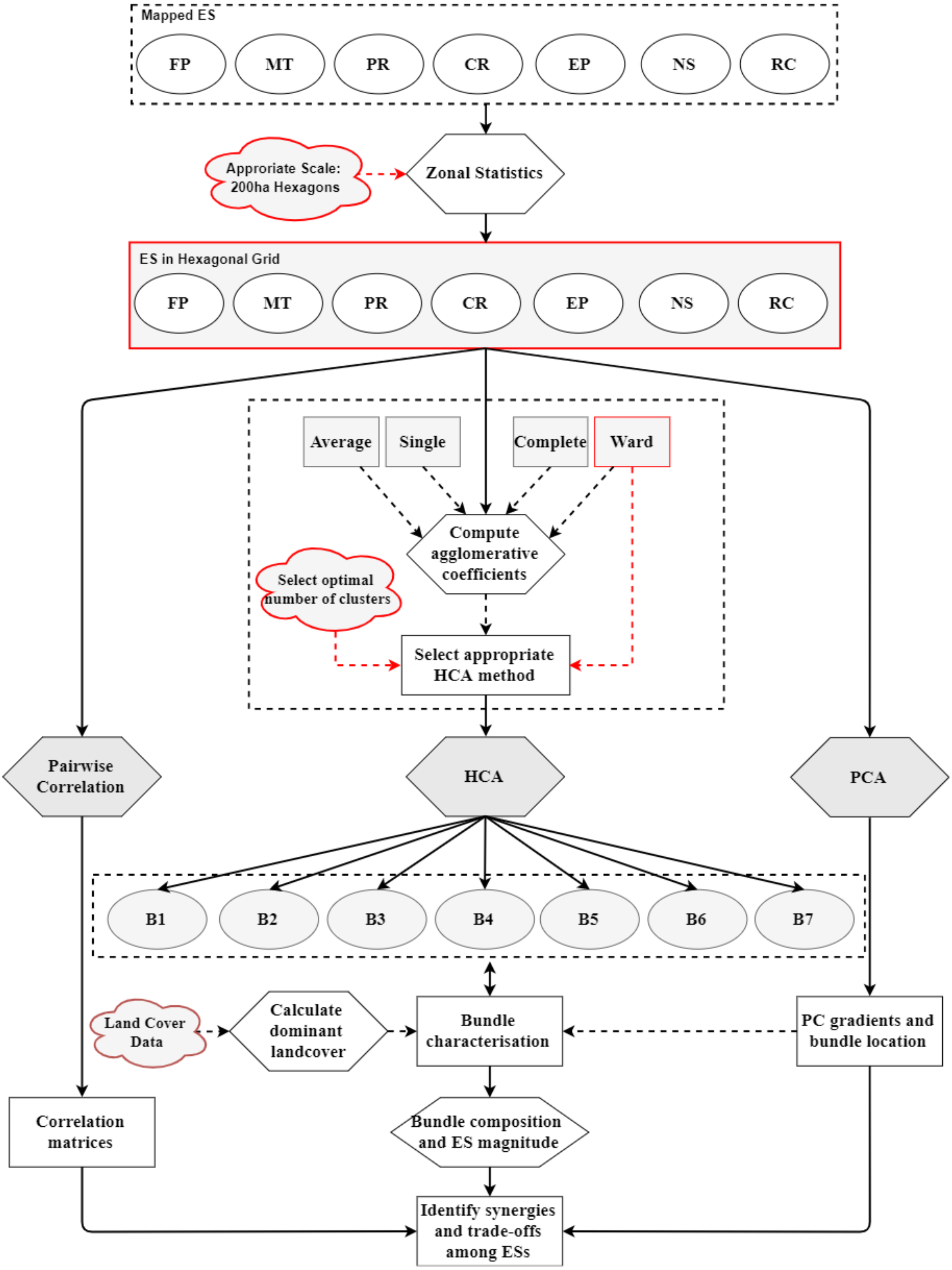


Figure 3.1: Schematic representation of the methodological flow chart used to identify interactions among ES. Source: adapted from Lorilla et al. (2018); FP: food provision; MT: materials from timber; PR: plant-based resources, CR: climate regulation, EP: erosion prevention; NS: maintenance of nursery populations and habitats; RC: recreation; HCA: hierarchical cluster analysis; PCA: principal component analysis; B1–7: ES bundles.

Pairwise correlation test for analyzing ecosystem service relationships

The Spearman rank correlation coefficient (Spearman ρ) is a non-parametric measurement correlation and it is used to determine the relation existing between two sets of data (Zar, 2005). Spearman correlation coefficients were calculated for all pairs of variables to investigate the direction (negative or positive) and the strength; $|\rho| > 0.5$ indicates strong relationship, $0.5 > |\rho| \geq 0.3$ indicates moderate relationship, and $|\rho| < 0.3$ indicates week relationship (Cui et al., 2019; Renard et al., 2015).

Cluster analysis for identifying ecosystem service bundles

A method used to create groups with similar characteristics is the agglomerative method Hierarchical Cluster Analysis (HCA) (Clarke & Warwick, 2001). A variety of agglomerative clustering methods exists from which the single linkage, complete linkage, average linkage, and Ward's hierarchical clustering method are commonly used. Before applying any hierarchical clustering, it is necessary to evaluate the dissimilarity values to specify the agglomeration technique to be used (Kaufman & Rousseeuw, 2008). One objective criterion to compare the clustering structure found by each technique is the agglomeration coefficients, which measures the amount of clustering structure of the ES values; the closer to 1, the stronger the clustering structure (Mojena, 1977). Therefore, the agglomerative coefficients of the single, complete, average, and Ward method were estimated. The most appropriate method was applied to assess the existence of ES bundles. The cluster dendrogram generated from HCA was classified into a number of classes (bundles) based on the elbow method for selecting the optimal number of classes. The elbow method is the oldest method for determining the true number of clusters in a data set and it involves running the algorithm multiple times over a loop, with an increasing number of cluster choice and then plotting a clustering score as a function of the number of clusters (Kodinariya & Makwana, 2013).

Ordination analysis for specifying ES relationships within bundles

To investigate the relationship among ESs within bundles, a principal component analysis (PCA) was performed to identify the proportions explaining ES variability by the two first axes. PCA also helped to visualize the location of each ES bundle in the PC gradients. Bundles were characterized by examining the dominant land cover of each formed bundle and its position in the gradients of the PCA axes. The composition of each ES bundle was presented using star plots and the magnitude was estimated using the mean value of each ES. Each petal in the star plot is associated with a single ES, where a longer length indicates higher ES supply.

3.4 Results on the spatial and temporal changes in ES supply

The results revealed different intensities and spatial patterns among the individual ES, as well as among the islands (Table 3.5). The cultural service of RC presented the higher intensities across the Ionian Islands, followed by MT, PR, and NS with moderate values, while FP, CR, and EP showed the lower intensities. The higher ES supply was found for RC in Corfu (0.70), while EP in Lefkada and CR in Zakynthos exhibited the lower values (0.19). The low values of CR and EP along with the moderate values of NS resulted in the overall lower intensity of Regulating and Maintenance ES. Similarly, the low value of FP and moderate values of MT and PR led to the moderate supply of provisioning supply, resulting in the value of Total ES not exceeding 0.44 in the case of Corfu (<0.38 in the other islands).

Table 3.5: Average values of ES supply for the 1985–2015 period. Source: adapted from Lorilla et al. (2018).

ES SUPPLY (MEAN OF 1985–2015)	CORFU	LEFKADA	KEFALONIA	ZAKYNTHOS
FP	**0.38**	0.27	0.22	0.35
MT	**0.55**	0.39	0.35	0.32
PR	**0.52**	0.43	0.38	0.48
PROVISIONING	**0.50**	0.39	0.36	0.39
CR	**0.33**	0.26	0.29	0.19
EP	**0.30**	0.19	0.23	0.24
NS	0.52	**0.57**	0.49	**0.57**
REGULATING & MAINTENANCE	**0.29**	**0.29**	0.28	0.26
CULTURAL (RC)	**0.70**	0.64	0.62	0.53
TOTAL	**0.44**	0.38	0.35	0.35

FP: food provision; MT: materials from timber; PR: plant-based energy resources; CR: climate regulation; EP: erosion prevention; NS: maintenance of nursery populations and habitats; RC: recreation; Numbers in bold indicate the highest ES supply among the Ionian Islands.

Food provision was mostly located in low land areas, showing both dispersed (Corfu and Lefkada) and clustered (Kefalonia and Zakynthos) patterns (Figures S6 – S9 in the Supplementary material). MT and PR followed a similar pattern where higher values covered areas across the extent of all islands. CR and EP were the least intensive ESs, and mainly covered mountainous and forested regions. NS did not show any specific spatial pattern, as this service had higher values throughout the studied areas. RC had different patterns of intensity, with this service being highly evident in the mountainous areas of some islands, while the mountainous areas of other islands had lower recreation supply. The three ES groups had similar spatial patterns within the extent of each Island (Figures 3.2 – 3.5). In Corfu, areas with higher values of provisioning and total ES supply were mainly located in the north and south parts, while lower supply was found in the north mountainous and the central regions (Figure 3.2). In contrast, RC followed a more evenly distributed pattern, as opposed to the patchier distribution of regulating ESs.

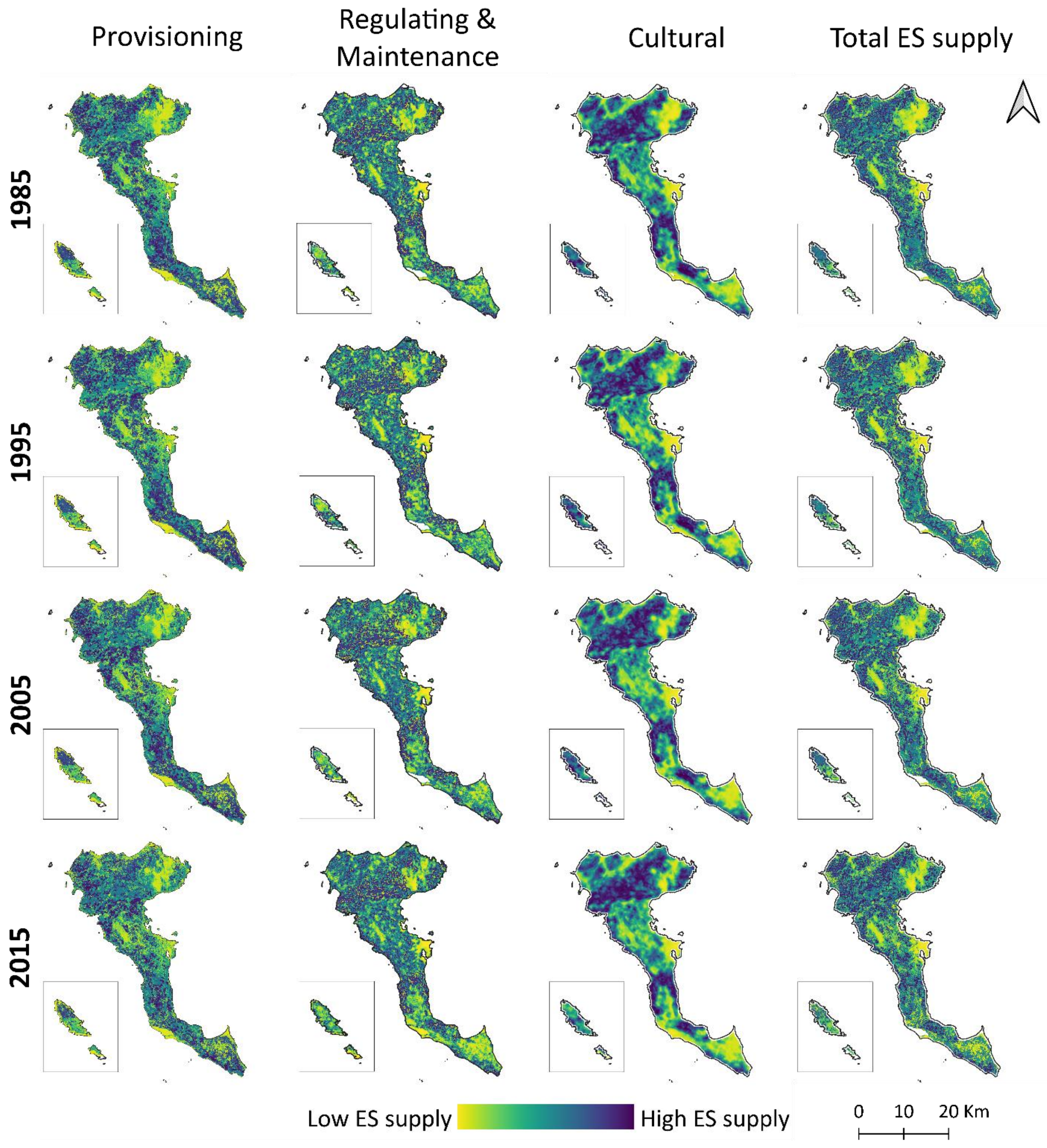


Figure 3.2: Temporal variations and spatial distribution of Provisioning, Regulating & Maintenance, Cultural and Total ES supply in Corfu. Source: own elaboration and adapted from Lorilla et al. (2018).

On Lefkada, provisioning ESs was dominant in the lowland areas, while higher regulating and maintenance ES supply was detected in regions where intermediate conditions of provisioning ES occurred. Recreation primarily occurred in the east, north, and south part of Lefkada Island and north of Kalamos Island. As for Total ESs, higher values covered mostly the north, northeast, and south part of Lefkada and the north parts of Meganisi and Kalamos (Figure 3.3). In contrast, lower Total ES supply was found in the central and southwest of Lefkada dominated by mountainous areas.

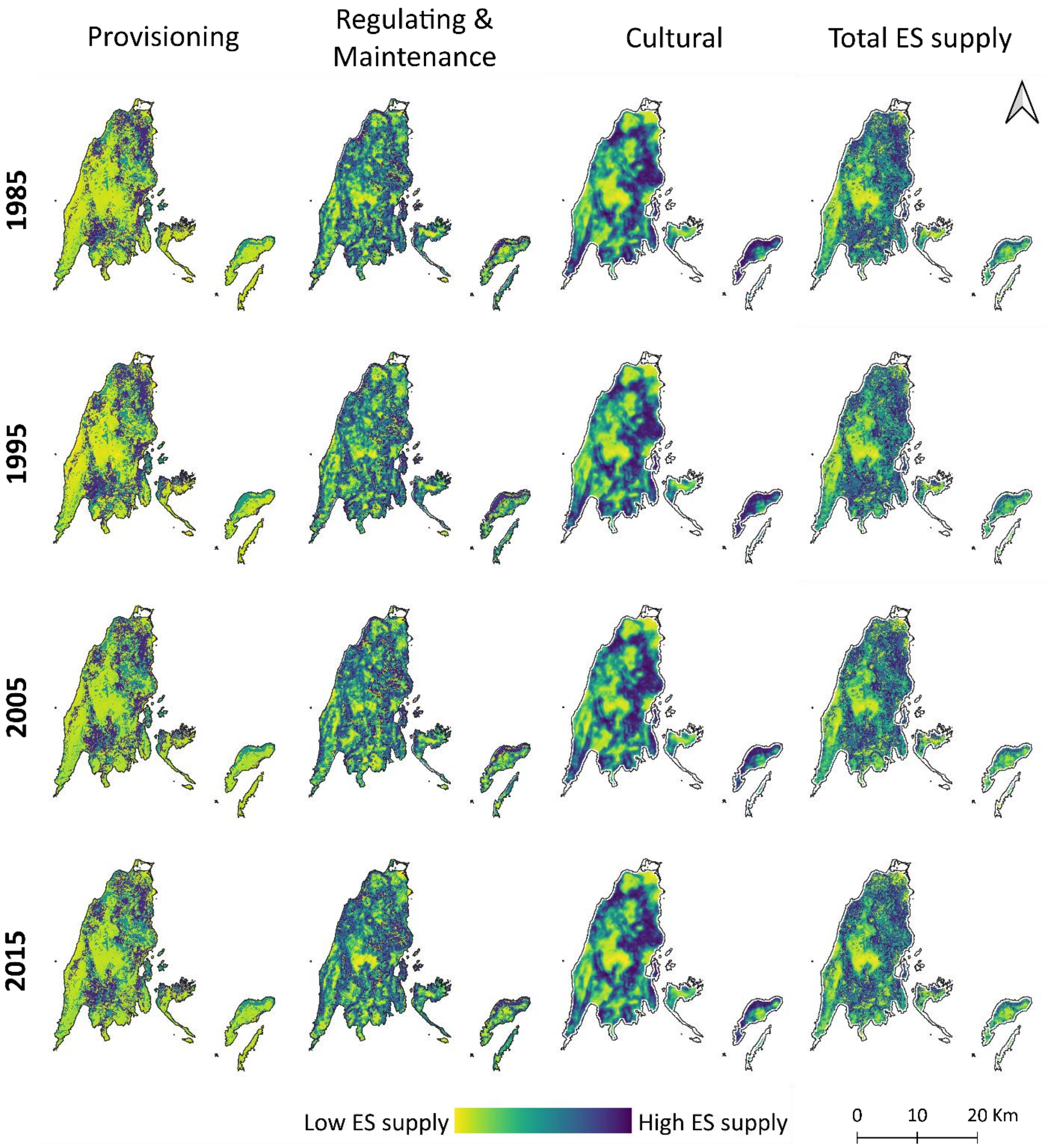


Figure 3.3: Temporal variations and spatial distribution of Provisioning, Regulating & Maintenance, Cultural and Total ES supply in Lefkada. Source: own elaboration and adapted from Lorilla et al. (2018).

Total ESs was evenly distributed across Kefalonia, except in the central part, where lower total ES supply occurred and was divided into two distinct homogeneous regions, with both higher and lower supplies of all ES groups (Figure 3.4). Most of the areas in this Island with lower provisioning ES supply, had a moderate to high supply of regulating and recreation ESs. In addition, higher values of total ES were located in the north and south parts of Ithaca Island.

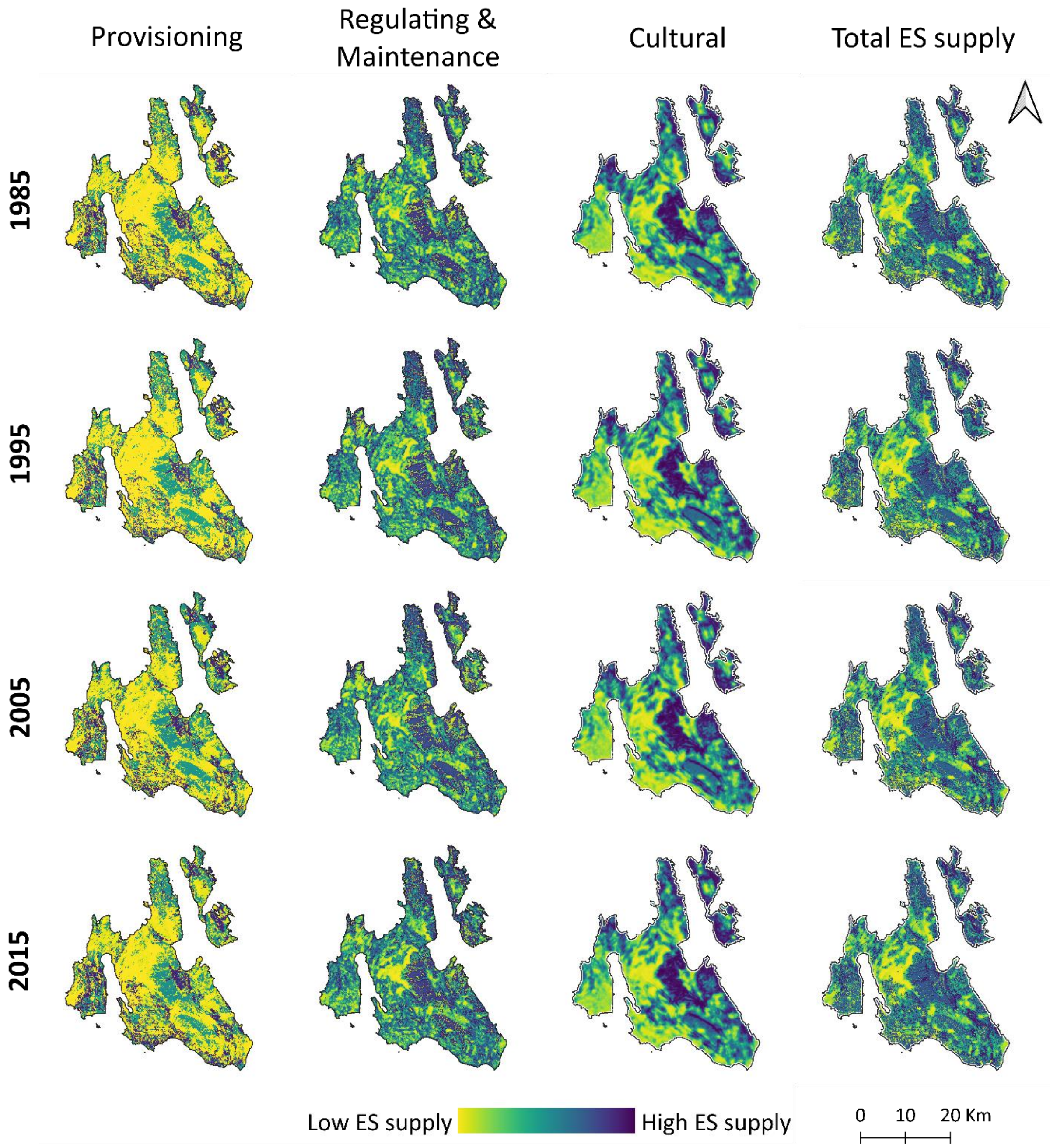


Figure 3.4: Temporal variations and spatial distribution of Provisioning, Regulating & Maintenance, Cultural and Total ES supply in Kefalonia (incl. Ithaka). Source: own elaboration and adapted from Lorilla et al. (2018).

Zakynthos was the only island where provisioning ESs had a different spatial distribution to that of regulating and maintenance ESs and recreation (Figure 3.5). Specifically, higher provisioning ES supply occurred in lowland areas, while lower values were located in the mountainous regions. Higher regulating and maintenance ESs and recreation were mainly located in mountainous areas, while higher total ES supply occurred both in mountainous and lowland regions. The lowland areas of Zakynthos had a homogeneous distribution of ESs, while mountainous areas were characterized by a patchier pattern.

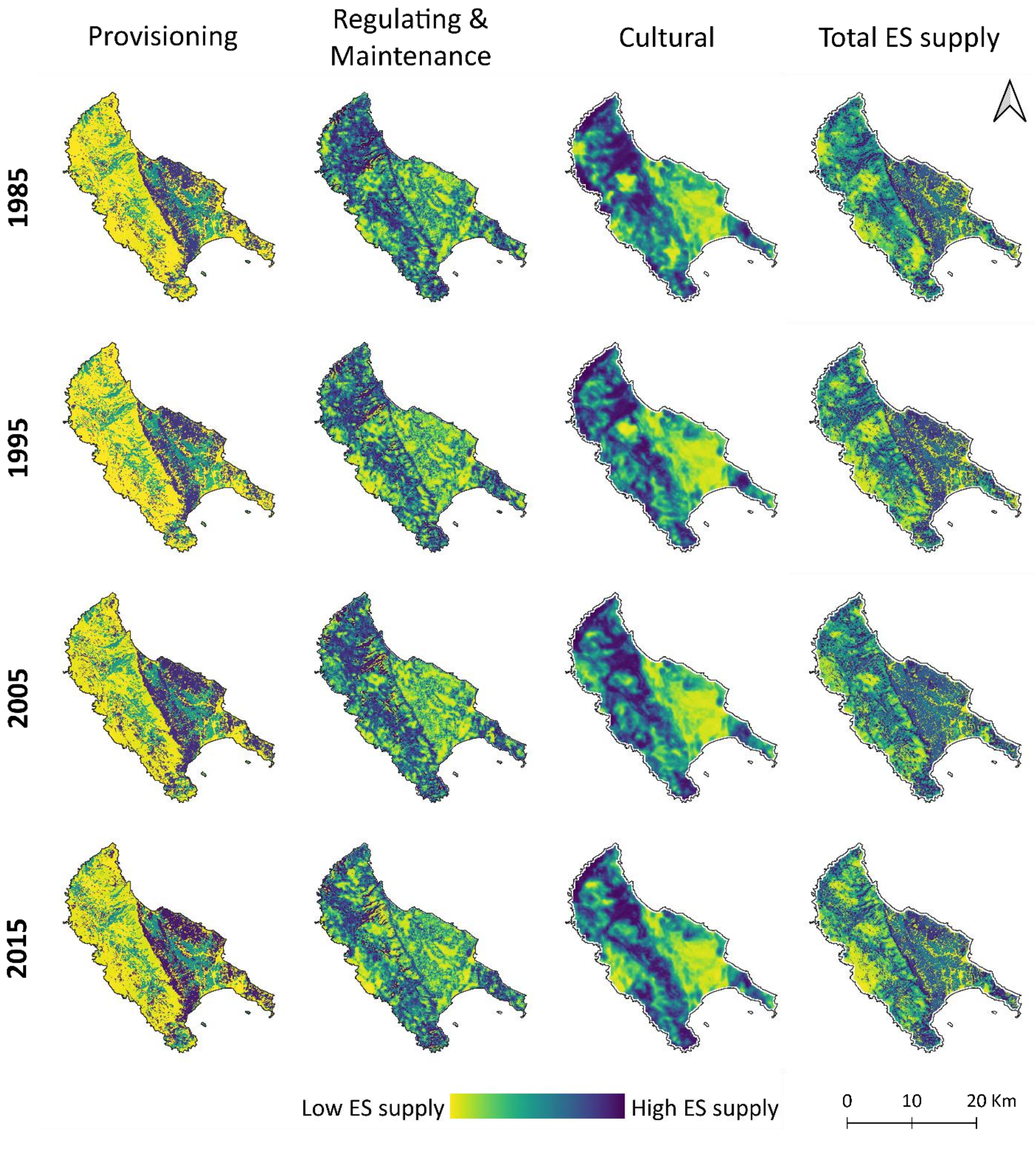
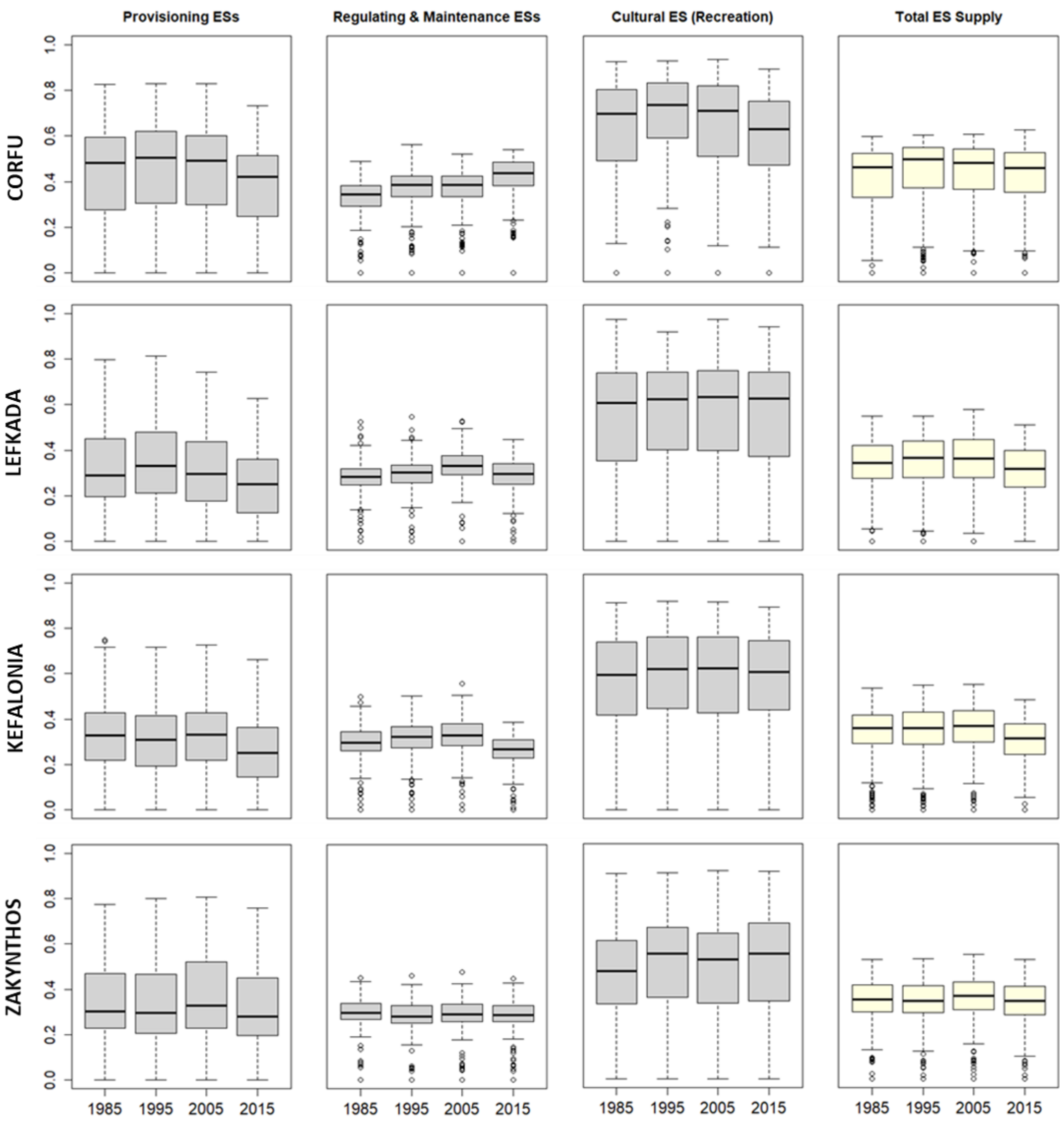


Figure 3.5: Temporal variations and spatial distribution of Provisioning, Regulating & Maintenance, Cultural and Total ES supply in Zakynthos. Source: own elaboration and adapted from Lorilla et al. (2018).

Concerning the temporal variations of ES groups (Graph 3.1), provisioning ES showed significant differences through the years across the region based on one way ANOVA (Corfu: [F(3,1668) = 14.19, $p < 0.001$]; Lefkada: [F(3,1092) = 15.77, $p < 0.001$]; Kefalonia: [F(3,2280) = 31.34, $p < 0.001$]; Zakynthos: [F(3,1036) = 3.37, $p = 0.018$]).



Graph 3.1: Mean values of ES supply for the three ES groups and the total ES supply. Source: own elaboration and adapted from Lorilla et al. (2018).

In general, provisioning ES in 2015 significantly decreased from the previous years throughout all Islands. Regulating ESs followed two different trends; an overall significant increase over time in Corfu [F(3,1668) = 80.41, $p < 0.001$] and Kefalonia [F(3,2280) = 75.06, $p < 0.001$], and an increase from 1985 to 2005 ($p < 0.001$) followed by a depletion in 2015 ($p < 0.001$) in Lefkada. Significant temporal differences of recreation was found in Corfu Island [F(3,1668) = 5.08, $p < 0.01$], which exhibited higher supply in 1995 compared to 2015 ($p < 0.01$), while there was no significant differences on the other three Islands ($p > 0.05$). Total ES supply showed a significant increase between 1985 and 1995 in Corfu ($p < 0.01$) and a significant overall decrease between 1995 and 2015 in Lefkada and Kefalonia ($p < 0.001$).

3.5 Results on the temporal changes in ES interactions and bundles

3.5.1 The interactions among ESs

Regarding spatial autocorrelation, the results showed that Moran's I was higher both for the 200ha hexagonal grid and the administrative grids (Table 3.6). In contrast, the 100ha hexagonal grid had the lowest Moran's I values. Although, the grid of municipal districts in Kefalonia presented higher spatial clustering in comparison with the other two grids, in Lefkada, the same grid reached an average of 0.19, indicating a low spatial clustering. On the other hand, the 200ha hexagonal grid in Corfu, Lefkada, and Zakynthos reached the higher values. Therefore, the latter grid, i.e. the 200 ha grid, was used as the scale of observation to identify ES interactions.

Table 3.6: Moran's I (M.I.) spatial autocorrelation results of the three different grids. Source: own elaboration and adapted from Lorilla et al. (2018).

ISLAND	YEAR	HEXAGONAL 100 HA			HEXAGONAL 200 HA			MUNICIPAL. GRID		
		M.I.	z-Value	p-Value	M.I.	z-Value	p-Value	M.I.	z-Value	p-Value
CORFU	1985	0.3517	15.1191	0.001	**0.5010**	16.4085	0.001	0.4353	6.6289	0.001
	1995	0.3009	13.1178	0.001	**0.4730**	15.6784	0.001	0.4132	6.3022	0.001
	2005	0.3227	13.9348	0.001	**0.5167**	16.7924	0.001	0.4367	6.5128	0.001
	2015	0.3097	13.5481	0.001	**0.4886**	15.8971	0.001	0.4037	5.9502	0.001
LEFKADA	1985	0.3809	12.9064	0.001	**0.4394**	10.3041	0.001	0.2615	2.6396	0.006
	1995	0.3798	12.7979	0.001	**0.4442**	10.4601	0.001	0.2099	2.1799	0.024
	2005	0.4142	13.6465	0.001	**0.4483**	10.6174	0.001	0.1891	1.9680	0.036
	2015	0.3955	13.1485	0.001	**0.5005**	11.7509	0.001	0.1176	1.3183	0.112
KEFALONIA	1985	0.1983	10.0153	0.001	0.3429	12.5241	0.001	**0.4295**	6.7134	0.001
	1995	0.2406	12.0775	0.001	0.4069	14.8225	0.001	**0.4982**	7.8021	0.001
	2005	0.2169	10.8401	0.001	0.4083	15.0074	0.001	**0.5063**	8.0189	0.001
	2015	0.2675	13.1031	0.001	0.4222	15.4819	0.001	**0.4531**	7.1961	0.001
ZAKYNTHOS	1985	0.3193	11.6542	0.001	**0.3681**	8.8311	0.001	0.3086	3.4895	0.003
	1995	0.3246	11.8395	0.001	**0.3723**	9.1376	0.001	0.3625	4.1015	0.001
	2005	0.3000	10.7004	0.001	**0.3267**	8.0560	0.001	0.3368	3.7379	0.001
	2015	0.3175	11.3667	0.001	**0.4235**	10.1869	0.001	0.3304	3.7096	0.001

Randomization: 999 permutations; Bold and underlined values indicate the highest Moran's I values, whereas gray squares indicate the lowest Moran's I values among the different grids.

The pattern of correlations for all islands was relatively similar in all four studied years (Figures 3.6 - 3.9); however, some ES pairs changed through time based on the direction and strength of their relationship. Overall, most ESs had a positive relationship over time in Corfu, Lefkada, and Zakynthos, while Kefalonia had the most negative correlations. Kefalonia had the most statistically significant correlations, contrary to Zakynthos, where the most non-significant ($p > 0.05$) relationships were found. The most positive relationships among regulating ESs occurred in Zakynthos, whereas the most negative relationships occurred in Kefalonia.

Among provisioning ESs (FP, MT, and PR), there were mainly strong and moderate positive correlations, especially in Zakynthos where all correlations were higher than 0.50. Only in Kefalonia, certain ES pairs (FP-MT and FP-PR) presented moderate and weak positive relationships ($r < 0.35$). The correlations among the regulating and maintenance ES (EP, CR, and NS) showed various results. Specifically, CR and EP demonstrated consistent positive correlations across islands and time, while weak correlations were found between EP and NS. The nursery service exhibited the most negative relationships amongst all ESs.

The relationship of provisioning ESs with regulating and maintenance ESs presented mostly positive correlations across the region, with Kefalonia and Zakynthos exhibiting some negative. The provisioning service of FP with the regulating services of CR and EP showed non-significant correlations through the years; however, a moderate negative correlation between FP and EP was observed in the last period on Kefalonia ($r = -0.41$). Positively strong relationships were identified between MT and CR across all Islands, while between MT and EP, strong positive correlations were found only in Corfu. The provisioning service of PR was positively correlated with all ES, except NS, where the stronger correlations occurred between PR and CR. The direction of the correlation for PR and NS varied among the islands. For example, in Corfu, a negative correlation became positive (−0.21 in 1995 to 0.10 in 2015), whereas a positive relationship between PR and NS led to a negative relationship in Zakynthos (from 0.15 to −0.27).

The recreation service showed a strong and moderate positive relationship with provisioning ESs (MT and PR), as well as with regulating ESs (EP and CR). Particularly in Corfu, RC was significantly positively correlated over time with MT, PR, EP, and CR, reaching coefficient values greater than 0.61, 0.58, 0.67, and 0.73, respectively. Among all islands, RC and FP presented both weak positive and negative relationships. Regarding RC and NS, different correlation patterns were found among the islands. In Corfu, the direction of correlation changed from negative (in 1995) to positive (in 2015). The positive relationship between RC and NS in Kefalonia became stronger, as opposed to Zakynthos, where the positive relationship tended to be weaker.

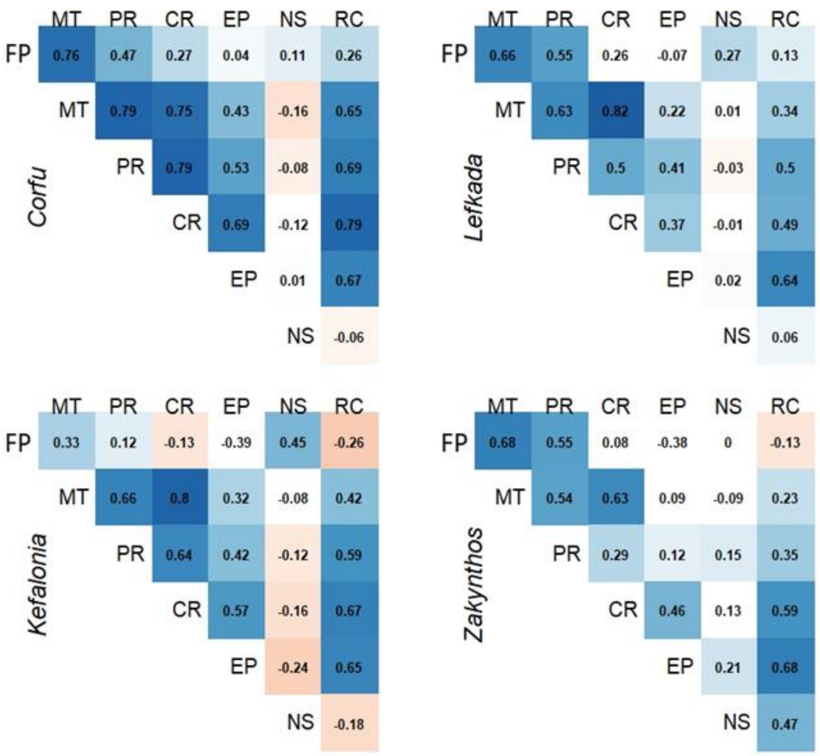


Figure 3.6: Spearman pairwise correlations between ESs in 1985. Source: adapted from Lorilla et al. (2018); Dark blue indicates strongly positive correlations defined as possible synergies and dark red indicates strongly negative correlations defined as possible trade-offs. White squares represent non-significant correlations ($p > 0.05$); FP: food provision; MT: materials from timber; PR: plant-based resources; EP: erosion prevention; CR: climate regulation; NS: maintenance of nursery populations and habitats; RC: recreation).

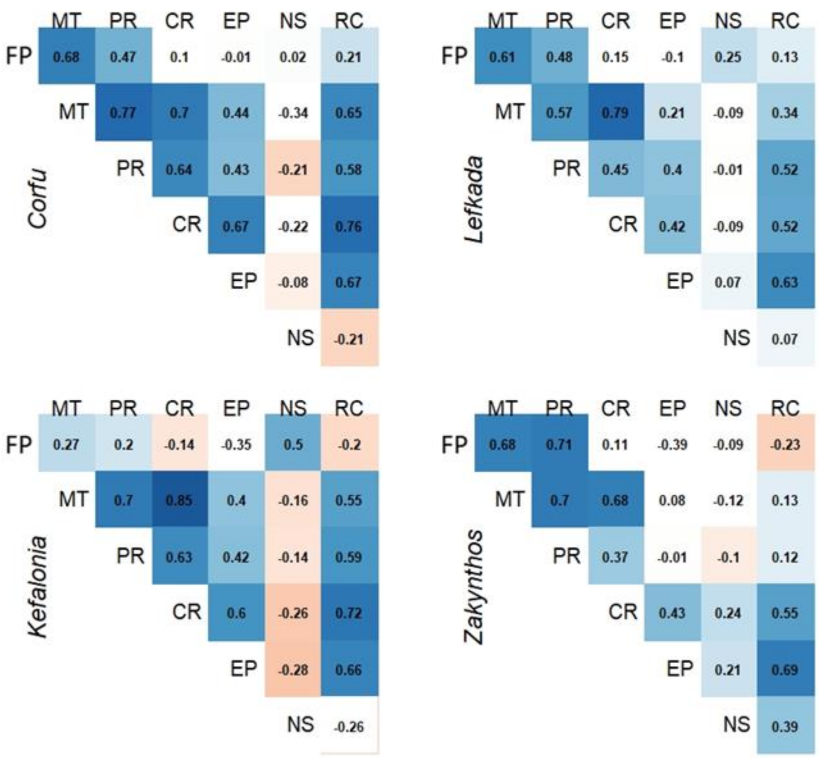


Figure 3.7: Spearman pairwise correlations between ES in 1995. Source: adapted from Lorilla et al. (2018); Dark blue indicates strongly positive correlations defined as possible synergies and dark red indicates strongly negative correlations defined as possible trade-offs. White squares represent non-significant correlations ($p > 0.05$); FP: food provision; MT: materials from timber; PR: plant-based resources; EP: erosion prevention; CR: climate regulation; NS: maintenance of nursery populations and habitats; RC: recreation).

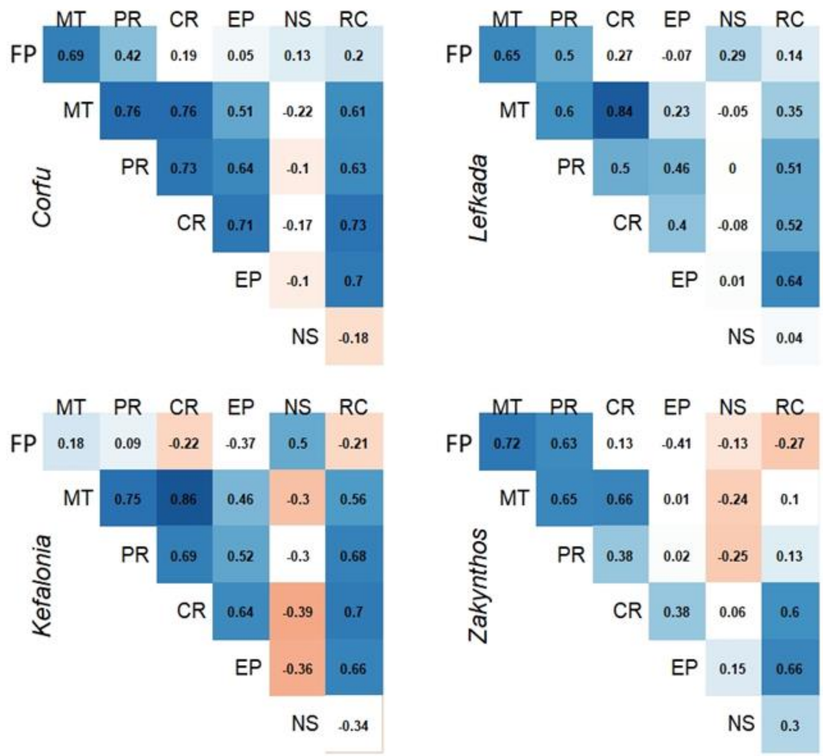


Figure 3.8: Spearman pairwise correlations between ES in 2005. Source: adapted from Lorilla et al. (2018); Dark blue indicates strongly positive correlations defined as possible synergies and dark red indicates strongly negative correlations defined as possible trade-offs. White squares represent non-significant correlations ($p > 0.05$); FP: food provision; MT: materials from timber; PR: plant-based resources; EP: erosion prevention; CR: climate regulation; NS: maintenance of nursery populations and habitats; RC: recreation).

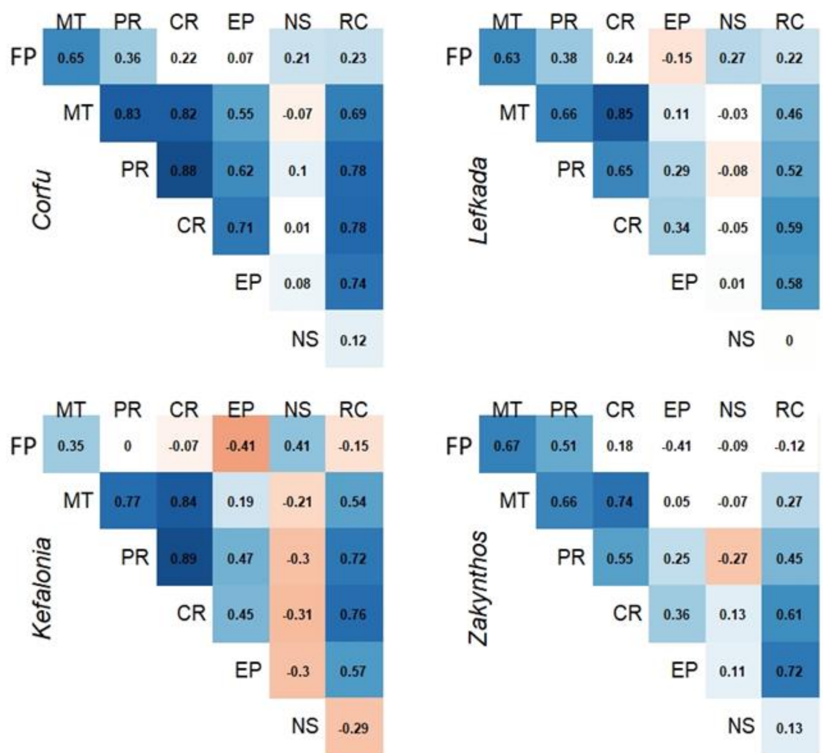


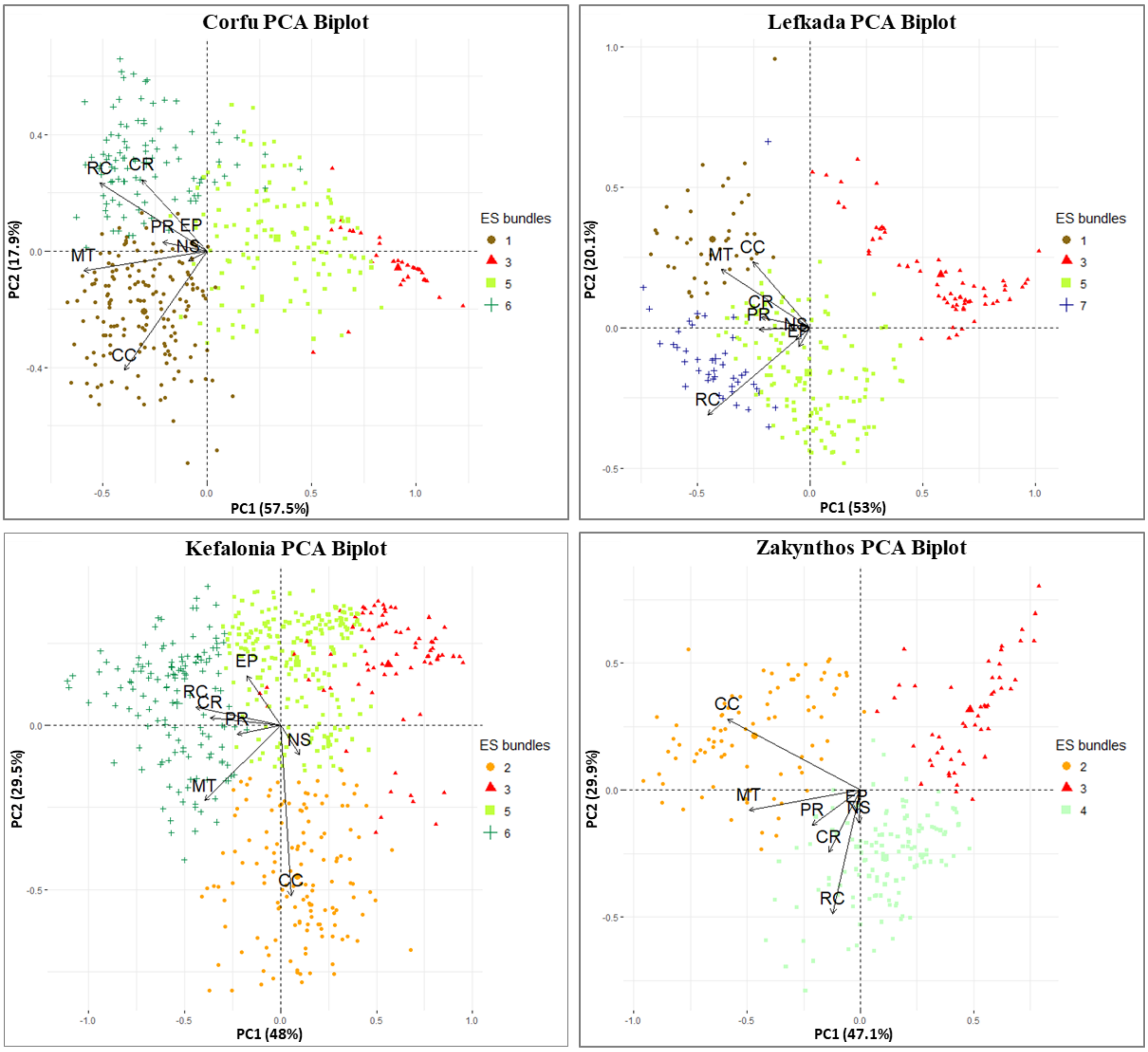
Figure 3.9: Spearman pairwise correlations between ES in 2015. Source: adapted from Lorilla et al. (2018); Dark blue indicates strongly positive correlations defined as possible synergies and dark red indicates strongly negative correlations defined as possible trade-offs. White squares represent non-significant correlations ($p > 0.05$); FP: food provision; MT: materials from timber; PR: plant-based resources; EP: erosion prevention; CR: climate regulation; NS: maintenance of nursery populations and habitats; RC: recreation).

3.5.2 The characterization of ES bundles

Regarding the four agglomerative methods, Ward's method presented the minimum cluster variance for all islands, because it overcame a 0.98 agglomerative coefficient followed by the complete method (0.94), average method (0.91), and single method (0.84). Hierarchical cluster analysis formed a total of seven ecosystem service bundles, from which four were identified in Corfu, four in Lefkada, four in Kefalonia, and three in Zakynthos (Figure S10 in the Supplementary material).

The first two PCA axes explained 75.4% of the ES variability for Corfu, 73.1% for Lefkada, 77.5% for Kefalonia, and 77% for Zakynthos, respectively (Graph 3.2). The first gradient in Corfu corresponded to an axis that ranged from olives with high recreation supply to low ES supply. The second gradient identified an axis from cultivated crops to areas with high recreation. The first gradient on Lefkada ranged from mixed olives with high recreation to low ES supply, while the second gradient presented a variation from diverse landscapes of high recreation to olive crop provision. The first axis, identified in Kefalonia, represented a forest recreation to low ES supply gradient, while the second gradient showed an agricultural to erosion prevention gradient. Finally, the gradients identified on Zakynthos were associated with an agricultural to low ES supply (PC axis 1) and recreation to cultivated crops (PC axis 2).

According to their location along the gradients in Graph 3.2, and the dominant land cover, ES bundles were characterized as olive groves (B1), high agricultural provision (B2), non-vegetated-low supply (B3), mountainous areas (B4), naturally vegetated areas (B5), forest recreation (B6), and high naturalness (B7). Specifically, B1 found in Corfu and Lefkada was located on the gradients where high provision of MT and FP occurs (PCA axis 1) and the dominant land cover was olive crops. The other agricultural bundle (B2) was found on the second axis of Kefalonia and on the first axis of Zakynthos, where areas with various crop provision dominated this bundle. The bundle dominated with urban and open areas (B3) was found on all islands, and was located on the part of PCA axis 1 where ES were not correlated. In Zakynthos, B4 was characterized by a habitat mosaic (forests, transitional vegetation, shrubs, sparse vegetation, and open areas) that occurred in mountainous areas where recreation was evident. Shrub woods, transitional vegetation, high-density olives, and forests dominated B5, where, in Corfu, no specific ESs occurred. In comparison, in Lefkada and Kefalonia mostly regulating ESs took place in B5. The dominant land cover of B6 consisted of forested areas and were located along gradients with high recreation. Finally, B7 was only found in Lefkada, and was placed on the high recreation part of PCA axis 1, where forest, high-density olives, and shrubbery cover were dominant.



Graph 3.2: PCA gradients and bundle location (each point represents a hexagonal unit). Source: adapted from Lorilla et al. (2018); FP: food provision; MT: materials from timber; PR: plant-based resources; CR: climate regulation; EP: erosion prevention; NS: maintenance of nursery populations and habitats; RC: recreation.

In Table 3.7, the spatial changes of ES bundles over time are presented with the area percentage for each studied year. B1 and B2 (crop related bundles) remained stable over time except in Lefkada where the areas covered with olive groves declined 10% with a subsequent increase of B5 (naturally vegetated areas). Non-vegetated areas (B3) decreased in Corfu and Lefkada and increased in Zakynthos, while in Kefalonia remained relatively similar. Mountainous areas (B4) had a depletion of 5% from its original state in 2015. Areas with high potential for forest recreation (B6) in Corfu increased throughout all of the studied years, as well as in Kefalonia from

1985 to 2005. However, in 2015, B6 in Kefalonia decreased by almost 4%. The last bundle (B7) represented areas with high naturalness due to the existence of forest, shrubbery, and high-density olives, which decreased by 13% between 1985 and 1995, but then increased to 17% in 2015.

Table 3.7: Changes in the percentage area (%) covered by each ES bundle over time. Source: own elaboration and adapted from Lorilla et al. (2018).

	CORFU				LEFKADA				KEFALONIA				ZAKYNTHOS			
	1985	**1995**	**2005**	**2015**	**1985**	**1995**	**2005**	**2015**	**1985**	**1995**	**2005**	**2015**	**1985**	**1995**	**2005**	**2015**
B1	45.4	48.1 ↗	47.9 ↘	45.8 ↘	31.7	32.8 ↗	22.7 ↘	21.7 ↘								
B2									27.4	25.8 ↘	26.4 ↗	26.4 →	35.8	34.1 ↘	36.7 ↗	35.7 ↘
B3	7.3	3.5 ↘	1.9 ↘	2.6 ↗	7.2	3.9 ↘	3.3 ↘	4.6 ↗	3.5	3.1 ↘	3.6 ↗	5.2 ↗	5.6	2.6 ↘	2.0 ↘	11.0 ↗
B4													58.6	63.3 ↗	61.4 ↘	53.3 ↘
B5	23.7	23.5 →	26.1 ↗	25.7 ↘	34.9	49.9 ↗	57.2 ↗	56.6 ↘	41.7	40.5 ↘	40.3 →	42.2 ↗				
B6	23.6	24.9 ↗	24.2 ↘	25.9 ↗					23.7	30.0 ↗	30.2 →	26.3 ↘				
B7					26.2	13.4 ↘	16.8 ↗	17.0 →								

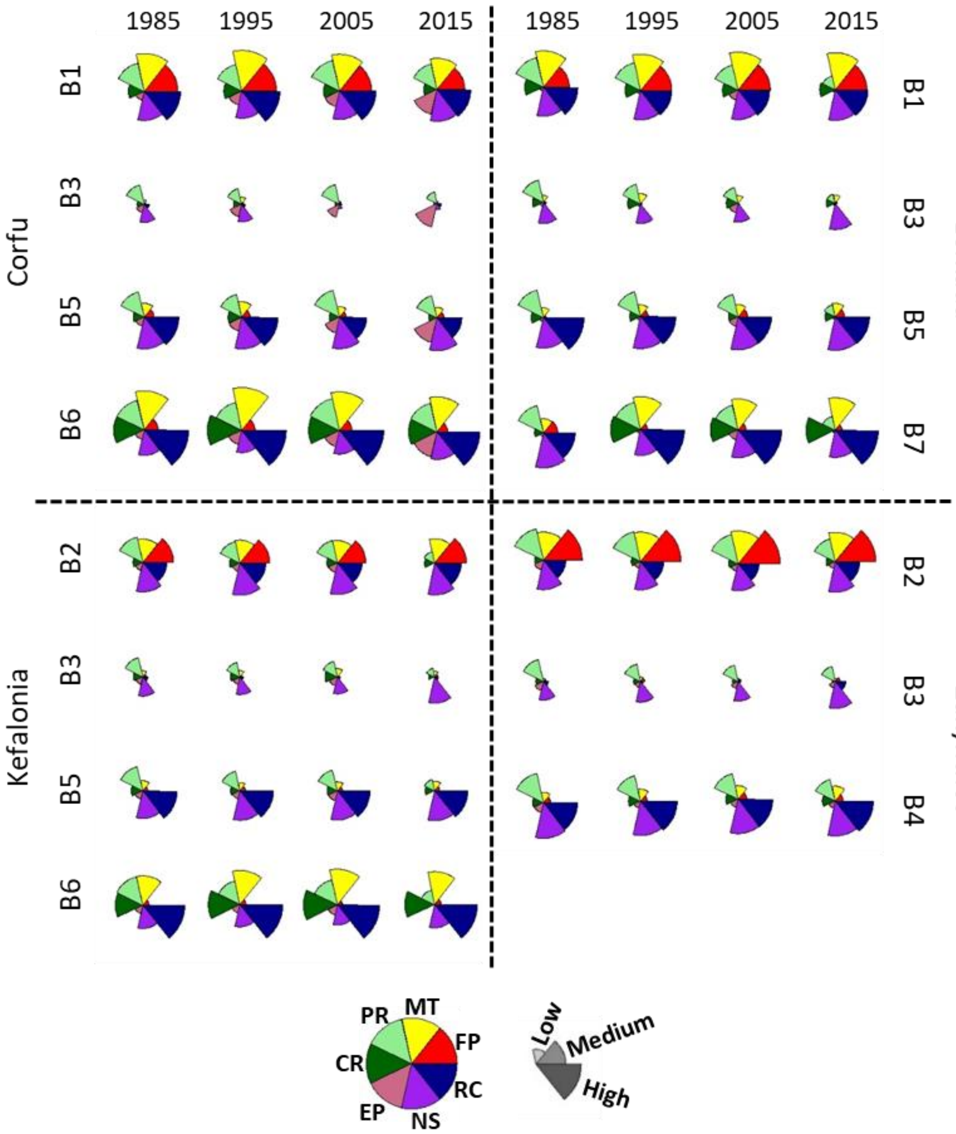
B1: olive groves; B2: high agricultural provision; B3: non-vegetated-low supply; B4: mountainous areas; B5: naturally vegetated areas; B6: forest recreation; B7: high naturalness.

3.5.3 The magnitude and composition of ES Bundles

Overall, Zakynthos appeared to have the most stable bundle composition and magnitude through time, followed by Kefalonia (Table 3.7 and Graph 3.3). Within all ES bundles, there were small variations among the studied years, with the magnitude of few ESs changing.

In the olive grove bundle (B1), MT, FP, NS, and RC had high provisioning, indicating synergies among them. Within B1 in Corfu, the magnitude of MT decreased over time, while EP increased. In comparison, in Lefkada, PR tended to decline. Agricultural areas (B2) in Kefalonia mainly provided FP and NS with other services also occurring (RC and MT). The high presence of provisioning ESs were evident in the agricultural bundle of Zakynthos. In both Zakynthos and

Kefalonia, PR in B2 decreased by 2015. As for non-vegetated areas (B3), they presented low ES supply on all islands. The mountainous bundle (B4) was only found in Zakynthos, and had a similar pattern with the naturally vegetated areas (B5) of Lefkada and Kefalonia, where NS and RC were the dominant, while PR decreased through the years. In the B5 of Corfu, the initial intensity and dominance of NS was retained, whereas EP increased and RC decreased. Corfu's forest recreation bundle (B6) presented an increasing magnitude of NS and EP, resulting in the provision of multiple ESs in 2015. In the forested areas (B6) of Kefalonia and in the high naturalness bundle (B7) of Lefkada, the supply of PR changed (from high in 1985 to low in 2015) and EP was almost absent. In both B6 and B7, RC had the highest supply, while FP was low or non-existent.



Graph 3.3: Dynamic magnitude of ES bundles. Source: adapted from Lorilla et al. (2018); B1: olive groves; B2: high agricultural provision; B3: non-vegetated-low supply; B4: mountainous areas; B5: naturally vegetated areas; B6: forest recreation; B7: high naturalness; FP: food provision; MT: materials from timber; PR: plant-based resources; CR: climate regulation; EP: erosion prevention; NS: maintenance of nursery populations and habitats; RC: recreation.

3.6 Discussion

3.6.1 Spatial distribution of ES supply

The spatial distribution of ESs in three islands (Corfu, Lefkada, and Kefalonia) followed a similar spatial pattern, where provisioning ESs, regulating and maintenance ESs, and recreation were spatially co-occurring. This finding contrasted with that of Queiroz et al. (2015), who found substantial differences in the distribution of provisioning, regulating, and cultural ESs. On Zakynthos only, provisioning ESs were distributed differently in relation to the other two ES groups, supporting a study conducted to an Alpine-wide level (Egarter Vigl et al., 2017b), in which provisioning ESs was found to be clustered in different areas to those where regulating and cultural ESs occur. All three ES groups exhibited significant differences in their temporal variation over time in Corfu only, whereas provisioning ESs and recreation followed a similar decreasing trend and regulating services increased. These results might be due to the loss of forests and high-density olives (Kefalas et al., 2018).

In addition to tourism, agriculture is an important sector of the economy in the Ionian region, which explains the high presence of provisioning ESs. Across the study area, olive orchards cover most of the agricultural regions, with other crop types (vineyards, arable, and mixed crops) also contributing to the supply of provisioning ESs. In addition, areas with a high supply of provisioning ESs are characterized by low elevation and flat topography (Lin et al., 2018; Raudsepp-Hearne et al., 2010; Turner et al., 2014), which was more prominent in Zakynthos, as higher elevated areas had a lower supply of provisioning services as opposed to the higher provision of lowland areas.

Regulating and maintenance ESs were higher in naturally vegetated and heterogeneous areas, supporting the results of previous studies (Bai et al., 2011; Barrios et al., 2018; Leh et al., 2013; Mouchet et al., 2017a). Specifically, forested regions present higher provision of regulating ESs (Egarter Vigl et al., 2017b; Queiroz et al., 2015), as shown in the case of the Ionian Islands with CR and EP. The nursery service (maintenance ES) was found in more diverse landscapes regardless of the type of vegetation. In Kefalonia, damage caused by forest fires 2007 (Iliadis et al., 2010), along with a decline in landscape diversity (Kefalas et al., 2019), might have caused the observed decline in regulating and maintenance ESs from 2005 to 2015.

The spatial pattern of recreation supply in each of the Islands was dependent on the amount of high-quality vegetation due to the higher weight value given to the degree of naturalness for mapping recreation. In Ionian Islands, a distinct mosaic of forest and olive yards is a characteristic landscape (Kefalas et al., 2018), mainly in Corfu and Lefkada, giving an extra value in the recreational service. Lower values of recreation were found in Zakynthos, due the low coverage of forests and less diverse landscape. These results were consistent with the findings of De Valck et al. (2017), where in a mixed landscape including farmlands and forests, diversity was highly appreciated from recreationists.

3.6.2 Spatial and temporal variations in ES interactions and bundles

The results demonstrated that ES relationships may change over time. Similar results were obtained by Renard et al. (2015), who showed clear evidence of the dynamics of ESs. However, the general pattern for the type and strength of the ES relationships was similar among the Ionian Islands, with some exceptions. Mostly positive correlations were found across the region, with Corfu having the strongest synergies and Kefalonia being subject to the most trade-off interactions. Among provisioning ESs there were positive correlations, suggesting a synergistic relationship, such as the one discussed by Turner et al. (2014). Regarding the relationships between provisioning and regulating ESs on a diverse landscape, Kong et al. (2018) found that crop production had a significantly strong negative correlation with soil retention. However, a similar finding was only evident in Lefkada for one year (2015), where food provision showed a moderate trade-off relationship with erosion prevention. In another study, Swallow et al. (2009) found no significant relationship between sediment yield and agricultural production. As for the relationship between provisioning and cultural ESs, food provision and recreation presented consistently positive correlations, as in the case of Corfu and Lefkada. This phenomenon might be explained by agricultural land abandonment, since Queiroz et al. (2015) connected the absence of strong negative trade-offs between agricultural and cultural services with a mosaic of mixed habitats. In contrast, in Kefalonia and Zakynthos, food provision and recreation showed an antagonistic relationship, which has also been detected by other studies (Maes et al., 2012b; Raudsepp-Hearne et al., 2010; Renard et al., 2015; Turner et al., 2014), possibly due to the intensification of agricultural practices. These patterns further enhance the association of mixed olives and forests with the high supply of ES (Brunori et al., 2018; Jose, 2009).

The ES assessment followed in this chapter, presented various correlations and facilitated the formation of ES bundles. In total, seven ES bundles were formed in the Ionian Islands, from which agricultural and forested bundles were also identified in other studies, indicating that there is a general pattern in the formation of ES bundles. Specifically, each Ionian Island formed one bundle of agricultural use (B1 in Corfu and Lefkada, and B2 in Kefalonia and Zakynthos), supporting the results of previous studies (Crouzat et al., 2015; Lin et al., 2018). In comparison, other studies identified two crop-related bundles in a single study area (Queiroz et al., 2015; Raudsepp-Hearne et al., 2010; Renard et al., 2015). Most of these existing studies recognized agricultural cover as the dominant bundle, which was only the case for the olive grove bundle (B1) in Corfu. However, the agricultural bundles still covered a large amount of land in the Mediterranean ecosystems of the Ionian Islands. In addition, this bundle in Corfu provided a set of multiple ES (including all ES groups) through the years, which contrasted with other agricultural bundles (Kong et al., 2018; Raudsepp-Hearne et al., 2010; Renard et al., 2015). In Zakynthos, despite the increase in the tourism industry and population density (Kefalas et al., 2018), the agricultural bundle varied across years, but retained a stable extent and supply of provisioning ESs. However, in the case of an another Greek Mediterranean island, declines in the agricultural sector were linked to increasing tourism (Tzanopoulos & Vogiatzakis, 2011). Kefalonia presented an interesting result, not found in other studies, where the agricultural bundle provided a similar and higher magnitude of recreation than provisioning ESs. Also, seasonal variations might occur in the agricultural bundles, since different crop types are harvested in specific times of the year (i.e., vineyards are harvested in the summer season, while olive groves in the fall or winter season).

The developed bundle covered mainly by rocky, open, and urban areas occupied the smallest extent in all islands and provided a negligible amount of ES over the studied years, with similar results being obtained for other urban bundles (Baró et al., 2017). However, these findings also contrasted with other studies, in which urban bundles provided a set of ESs related to provisioning and regulating ESs and, in some cases, cultural ESs (Queiroz et al., 2015; Raudsepp-Hearne et al., 2010). The stable composition and magnitude of the non-vegetated bundle in Zakynthos and Kefalonia might be due to their supporting similar livestock densities, as discussed by Kefalas et al. (2018).

The mountainous bundle found only in Zakynthos was characterized by a diversity of forest, transitional vegetation, shrublands, sparse vegetation, and, even, rocky and open areas, explaining the high supply of nursery and recreation. This result was obtained because the diversity of landscapes was a key indicator for these two services. Similarly, in the mountainous bundle obtained by Yang et al. (2015), forest recreation had a high supply. However, in this previous study, regulating services were also highly evident in mountainous areas, as opposed to the low regulating ES supply in Zakynthos. Similar to the non-vegetated bundles in Zakynthos, the maintenance of livestock densities resulted in the stable composition and ES magnitude of the mountainous bundle.

It is clear that, within a region, and especially an Island complex, different ES patterns occur, both among islands and at a temporal scale. For example, in Kefalonia, between 1985 and 1995, the agricultural bundle and the naturally vegetated bundle decreased in size, while forest areas increased, suggesting a lack of disturbance. In comparison, a different profile appeared between 2005 and 2015, where a depletion of forest ecosystems (decrease of B6) and gain in rocky and open areas might have been caused by forest fires (Iliadis et al., 2010). Also, on Zakynthos, transitions between the non-vegetated bundles and the mountainous ecosystems might be explained by impacts from forest fires (Poirazidis et al., 2018). The progressive decrease in the non-vegetated bundle in Corfu with a subsequent increase in the olive grove bundle and the forest bundle might be explained by land abandonment in some areas and agricultural transition in others (Kefalas et al., 2019). Renard et al. (2015) found similar contrasting trajectories in a single study area (field abandonment and agricultural specialization), contributing to the changes to ES bundles. Post-fire vegetation regeneration could also be suggested as a driver in the observed patterns of Corfu; however, fire events were concentrated in the north mountainous areas, where only low density vegetation was evident (Kefalas et al., 2018).

To manage ecosystems sustainably, knowledge about how ESs vary at spatial and temporal scales is required. This chapter also showed the similarities and differences in the distribution and interactions of ES among the Ionian Islands. Provisioning, regulating, and recreation ESs present spatial congruence in some islands, as opposed to others, where provisioning ES followed different pattern in relation to regulating ESs and recreation. In addition, the mountainous areas of Lefkada were occupied by lower total ES supply due to the absence of natural vegetation, whereas the mountainous regions of Kefalonia had moderate to higher total ES values. The contribution of mixed olive trees with natural vegetation played a key role in these patterns. Overall, recreation was dominant in relation to provisioning and regulating ES, as the islands are characterized by high natural and diverse ecosystems.

This chapter also demonstrated that interactions among ESs were not static and changed over time, probably as a result of changing spatial policies directly affecting land cover. Agricultural production, land abandonment, increasing tourism, and frequent forest fires might represent the main factors driving trajectories in ES relationships and among ES bundles. The formed ES bundles had distinct compositions and magnitudes, but these were highly dependent on the selected ES and mapping methods. However, similar results were observed in other study areas, indicating the formation of key ES bundles across different landscapes. Areas dominated by olive groves delivered the most ES with high magnitude, showing high synergies within these regions, due to the complex ecological processes that are needed to maintain such ecosystems. These findings provide useful information on the dynamic nature of ESs in Mediterranean island ecosystems, which can be used by stakeholders, decision- and policy-makers for promoting sustainable resource management and planning. Knowledge on the spatial and temporal changes of ES supply and interactions can improve the understanding of underlying processes affecting these changes and optimize the provisioning of multiple ESs.

CHAPTER FOUR

4 MAXIMIZING THE SPATIAL CONGRUENCE BETWEEN ECOSYSTEM SERVICE SUPPLY AND DEMAND[4]

"The imbalance between socially driven economic growth on the one hand and the naturally limited availability of resources on the other poses one of the biggest challenges of our time."
- Syrbe and Grunewald (2017), Int J Biodiv Sci, Ecosyst Serv and Manage

4.1 Contextual background

The concept of ecosystem services (ESs) links ecosystem functions to human interests, with great potential to influence environmental decisions (Villamagna et al., 2013). According to the MEA (2005), ESs are in short supply due to the growth of human demands. In addition, ES provision is highly influenced by the availability and accessibility of ES supply, which means that little or no supply, may lead to unfulfilled demand (Wolff et al., 2017). To maintain the provision of multiple ES, ES must be consistently used under a regime that balances supply and demand. The demand and consumption of ESs today far exceed actual supply (Burkhard et al., 2012). The problem being the less known to the broader public unsustainable usage limits of ES resources. Furthermore, society must understand that users or managers of a land are not the actual service providers; instead, they must facilitate the functioning of ecosystem on their land to provide ESs and, where possible, enhance it (Syrbe & Walz, 2012). Consequently, a lack of awareness on the use of ESs could have severe impacts on both the natural environment and human well-being. Through distinguishing the supply and demand of ESs, it is possible to enhance the utility of ES mapping as a decision-support tool by informing policy-makers where ESs are used unsustainably and where it is sensible to invest in the maintenance of ESs (Baró et al., 2016; Geijzendorffer et al., 2015). Within this context, the current chapter explored the spatial congruence and mismatch between the supply of ESs and society's demand for ESs to optimize the design and decision-making process towards implementing appropriate planning actions that foster the sustainable use of ESs.

[4] Parts of this chapter have been published in the form of a scientific article. Citation: Lorilla, R. S., Kalogirou, S., Poirazidis, K., & Kefalas, G. (2019). *Identifying spatial mismatches between the supply and demand of ecosystem services to achieve a sustainable management regime in the Ionian Islands (Western Greece)*. Land Use Policy, 88, 104171.

4.2 Methodology for mapping ES similarities and mismatches

4.2.1 Data sources

This chapter focused on three ESs that were considered relevant for identifying ES mismatches in the Ionian Islands, including Food provision (FP), Climate Regulation (CR), and Recreation (RC) (Table 4.1). ES supply maps were derived from the analysis carried out in Chapter 3, where a set of biophysical indicators/proxies was estimated to map the capacity of the Ionian Islands to provide multiple ESs (i.e. ES supply). To map ES demand, the LULC datasets of the Ionian Islands for 2015 (similar to those used in Chapter 3) were used. These datasets were obtained by Kefalas et al. (2018), with high spatial and thematic accuracy over 85%,. The LULC classification scheme consisted of 16 terrestrial classes (Table S1 in Supplementary material), in which, in the cases of food provision and recreation, an economic value was assigned (Tables 4.2 and 4.3).

Table 4.1: List of the estimated supply and demand of ES and their relevant indicators/proxies. Source: adapted from Lorilla et al. (2019).

ECOSYSTEM SERVICE	SUPPLY INDICATOR	DEMAND INDICATOR
FOOD PROVISION	Land under cultivation	Market value of representative agricultural products
CLIMATE REGULATION	Below and above ground carbon storage	Market value of carbon emission permits
RECREATION	Recreation potential	Benefit value of LULC classes

The look-up tables of prices for selected representative products of the European Union (EU) were used to estimate the value of food provision (European Commission, 2019a, 2019b). The OpenStreetMap (OSM) dataset was acquired using the OpenStreetMap Plugin for QGIS (Andrade, 2015; OpenStreetMap Contributors, 2018), and was used as an additional source of information for quantifying the ES flow of recreation. The "raceway," "service," and "unclassified" categories from the OSM dataset were excluded from the analysis, as they refer to possibly restricted or non-accessible pathways for recreationists.

4.2.2 ES supply

The capacity of the Ionian Islands to supply cultivated plants or agricultural produce for human and animal consumption (i.e., food, fiber, and source energy) was mapped using the presence of land under cultivation [Chapter Three] (Lorilla et al., 2018). Climate regulation represents the capacity of vegetation to mitigate climate change (Cushman et al., 2006). Supply maps of climate regulation were created by assigning below and above ground carbon storage values (metric tons C/ha) to each LULC class. Recreation supply was estimated using a combination of four indicators (naturalness, geodiversity, landscape diversity, and the existence of protected areas) to estimate recreation potential [Chapter Three] (Lorilla et al., 2018).

4.2.3 ES demand

The demand for ESs was estimated through its economic valuation. The methods used for the economic valuation of the investigated ESs were the market price method for food provision and for climate regulation, and the benefit/value transfer method for recreation.

The market price method represents a primary valuation that consists of pricing ESs that are directly observed in markets, and may reflect human demand for specific ecosystem products (Heal, 2000). In addition, some environmental effects can be valued relatively easily, for example, air quality impacts on the quantity of agriculture production; this change in production can be valued using market prices (defra, 2007). Demand for food provision was estimated based on the market values of representative crop products, assuming that high demand for food provision is driven by high market values. In specific, the prices of representative agricultural products were assigned for each crop type (Table 4.2). For example, the LULC types of olive groves, vineyards, and arable land were given the mean annual price of five years in Euros per 100 kg or liters of olive oil, grapes (for wine) and wheat, respectively.

Table 4.2: Economic values (€) of food provision per crop type.

LULC CLASS	VALUE PER CROP TYPE
HIGH-DENSITY OLIVE ORCHARDS	241.78
MEDIUM-DENSITY OLIVE ORCHARDS	241.78
VINEYARDS	41.47
ARABLE LAND	163.71
MIXED CULTURES	41.47
OTHER CULTURES	163.71
PERMANENT CULTURES	49.63
URBAN	0.00

To quantify the demand for climate regulation, greenhouse gas emissions (GHG) provide a possible measure of the demand for carbon sequestration required to balance anthropogenic emissions. This approach has been previously used to quantify climate sequestration demand by multiplying population by emissions per capita (Bagstad et al., 2014) (Equation 4.1):

$$\boldsymbol{GHG\ emissions} = Populations\ per\ unit \times GHG\ emissions\ per\ capita \qquad [4.1]$$

ES demand for climate regulation was mapped using the latest population census data (Hellenic Statistical Authority, 2014) and the mean annual value of CO_2 emissions for Greece (6.27 metric tons per capita for 2015) (MEE, 2017). Furthermore, following previous studies (Häyhä et al., 2015; Paletto et al., 2015), the emission permits regulated by the European Union Emissions Trading Scheme were used to estimate the market value of climate regulation, using an average price of 6 €/t CO_2 (World Bank, 2015). However, due to the spatial scale of population data, the resulting map was generalized in administrative units. To create a continuous map of economic values for climate regulation demand, the data were disaggregated using the ESPON framework [Figure 4.1] (Milego & Ramos, 2013) based on a more detailed grid (30 x 30 m). Specifically, the land cover types were assigned certain weights according to the demand for each type in relation to climate regulation (Burkhard et al., 2012). The grid was then joined with the administrative layer to create a continuous layer of economic values for climate regulation demand. This scale transformation facilitated comparison among the three ES.

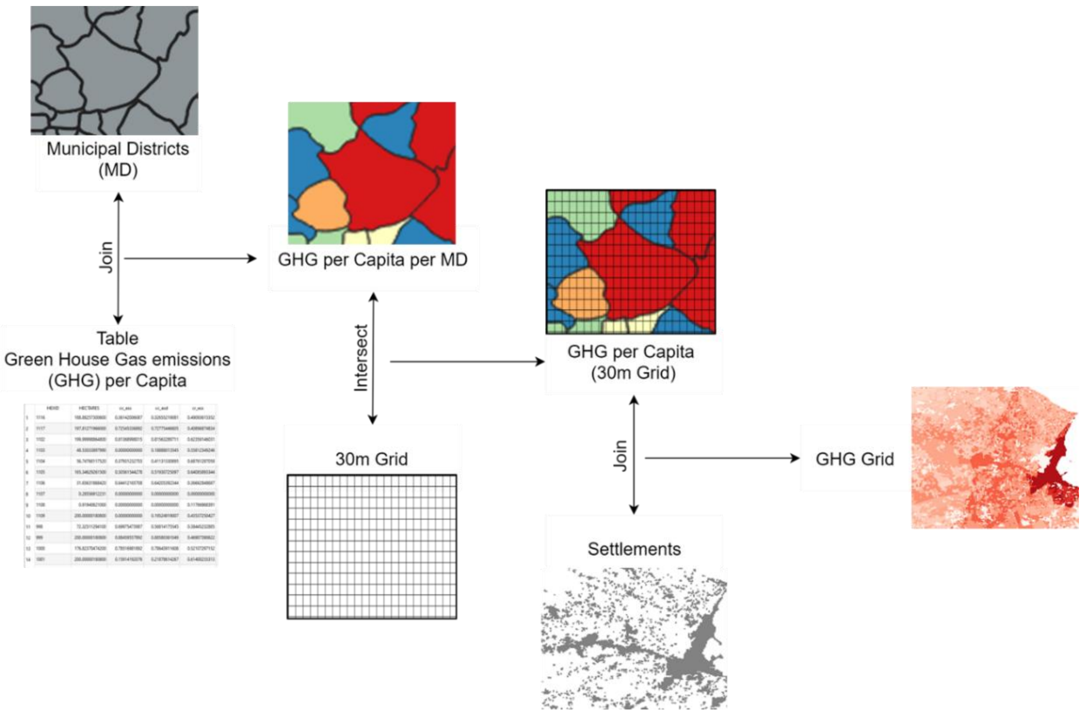


Figure 4.1: Disaggregation of emissions per capita per municipal district into a regular grid 30m. Source: own elaboration and inspired by Milego & Ramos (2013).

To value the ES of recreation, the benefit/value transfer approach was applied. The use of benefits transfer is an important issue in policy appraisal as it can reduce the need to conduct a primary valuation study. In this chapter a combination of databases was used to select previous ES valuation studies that were conducted in Mediterranean ecosystems The databases consisted of (1) the TEEB database (van der Ploeg et al., 2010), (2) the Environmental Valuation Reference Inventory – EVRI Database (https://www.evri.ca/), and (3) the Scopus Database of peer-reviewed literature (https://www.scopus.com/)]. The gathered values represented ES estimates for each ecosystem type (Table 4.3). In cases where more than one economic value was found, the average economic value was calculated.

Table 4.3: Economic values recreation per land cover type. Source: adapted from Lorilla et al. (2019).

LULC CLASS	value per ha per year	LULC CLASS	value per ha per year
Forest	152.17	**High-Density Olive Orchards**	38.47
Shrubland	687.13	**Medium-Density Olive Orchards**	38.47
Transitional Vegetation	687.13	**Vineyards**	38.47
Phrygana	59.97	**Arable land**	38.47
Sparse Phrygana	0.00	**Mixed Cultures**	38.47
Meadow	59.97	**Other Cultures**	38.47
Open Areas/Rocks	0.00	**Permanent Cultures**	38.47
Burnt	0.00	**Urban**	4333.70

The recreation service, however, is only provided if people located in areas with demand have access to supply areas, to carry out recreational activities. Thus, in addition to quantifying the demand for this specific ES, the density of roads and settlements were considered as an indicator to link the supply and demand of recreation spatially, and to estimate the final ES flow.

4.2.4 Spatial similarities and mismatches

To quantify the actual use of ES, the Ecological Supply-d\Demand ratio (ESDR) indicator was used. Li et al. (2016b) developed ESDR (Equation 4.2) to show the relationship between actual ES supply and human demand. This approach was also used by Chen et al., (2019a) and Chen et al., (2019b) to identify the supply-demand shortfalls and mismatches of ES to optimize management. As shown Chapter 2 and section 2.5.2 the ESDR index forms as follows:

$$\boldsymbol{ESDR} = \frac{ESS - ESD}{(ESS_{max} + ESD_{max})/2} \begin{Bmatrix} > 0, excess\ ESS \\ = 0, balance \\ < 0, excess\ ESD \end{Bmatrix} \quad [4.2]$$

where ESS and ESD are the actual supply and demand for a specific ES, respectively; ESS_{max} and ESD_{max} indicate the maximum value of supply and human demand for a specific ES, and are extracted from the corresponding ESS and ESD spatial layers, respectively. A positive ESDR value indicates an ES surplus, a value of zero indicates supply-demand balance, and a negative value indicates that supply does not meet demand (i.e., there is a shortfall).

4.3 Methodology for identifying excess ES supply or demand

4.3.1 Hotspot analysis

While the ESDR approach provides a detailed visualization (based on the cell size) of the spatial matches and mismatches between the supply and demand of ES, it also creates a speckled effect that might not be helpful to policy-makers. This phenomenon arises because an immediate intervention to specific cells in the actual environment might be challenging, or unfeasible, to implement; consequently, it might be useful to identify larger and homogenous zones to implement appropriate management measures.

To facilitate zoning in homogeneous regions, the study area was divided into a 200-ha hexagonal grid (as in Chapter 3), in which the mean value of ESDR was calculated. Subsequently the Getis-Ord Gi* statistic (Equations 2.7 and 2.8) was applied. The results of ESDR range from -1 to +1; thus, cold spots reflect areas with significantly higher demand than supply, while hot spots represent areas with significantly higher supply than demand. The resulting z-scores and p-values signify where features with either high or low values are spatially clustered (Li et al., 2016a). The p-value is a probability and z-scores are standard deviations of the studied variable; 0.01, 0.05, and 0.1 are typical probabilities, and <−1.65 or >+1.65, <−1.96 or >+1.96, and <−2.58 or >+2.58 are critical z-scores for 90, 95, and 99% confidence levels, respectively. P-values > 0.05 are usually defined as statistically significant (Li et al., 2017b).

The z-scores were classified into five categories of ES flow to visualize distinct zones of high, low, and intermediate need for the sustainable management of ESs. Hot spots and cold spots with confidence levels above 95%, were considered key areas of ES provision and demand; thus, z-values were categorized as "greater than +1.96," "from +1.65 to +1.96," "from -1.65 to +1.65," "from -1.96 to -1.65," and "lower than -1.96" for Zones 1, 2, 3, 4, and 5, respectively. For each zone, the average values of ES supply and demand were calculated and visualized through boxplots. Statistically significant differences in the average values of ES supply and demand among the zones were identified by using one-way ANOVA along with Games-Howell post hoc tests. The Games-Howell post hoc test was also used to identify the existence of statistically significant differences between ES supply and demand within each ES flow zone. In addition, to delineate the land cover characteristics of the five zones, the percentage of LULC categories was calculated within each zone.

4.4 Results on the identification of ES mismatches

4.4.1 ES supply and demand

Cropland areas showed high demand (i.e., high economic value) for all three ESs, but had a low supply of climate regulation and recreation (Figures 4.2 and 4.3). Olive groves, which are present on all islands, had the highest economic benefits, followed by permanent cultivations (i.e., fruit orchards).

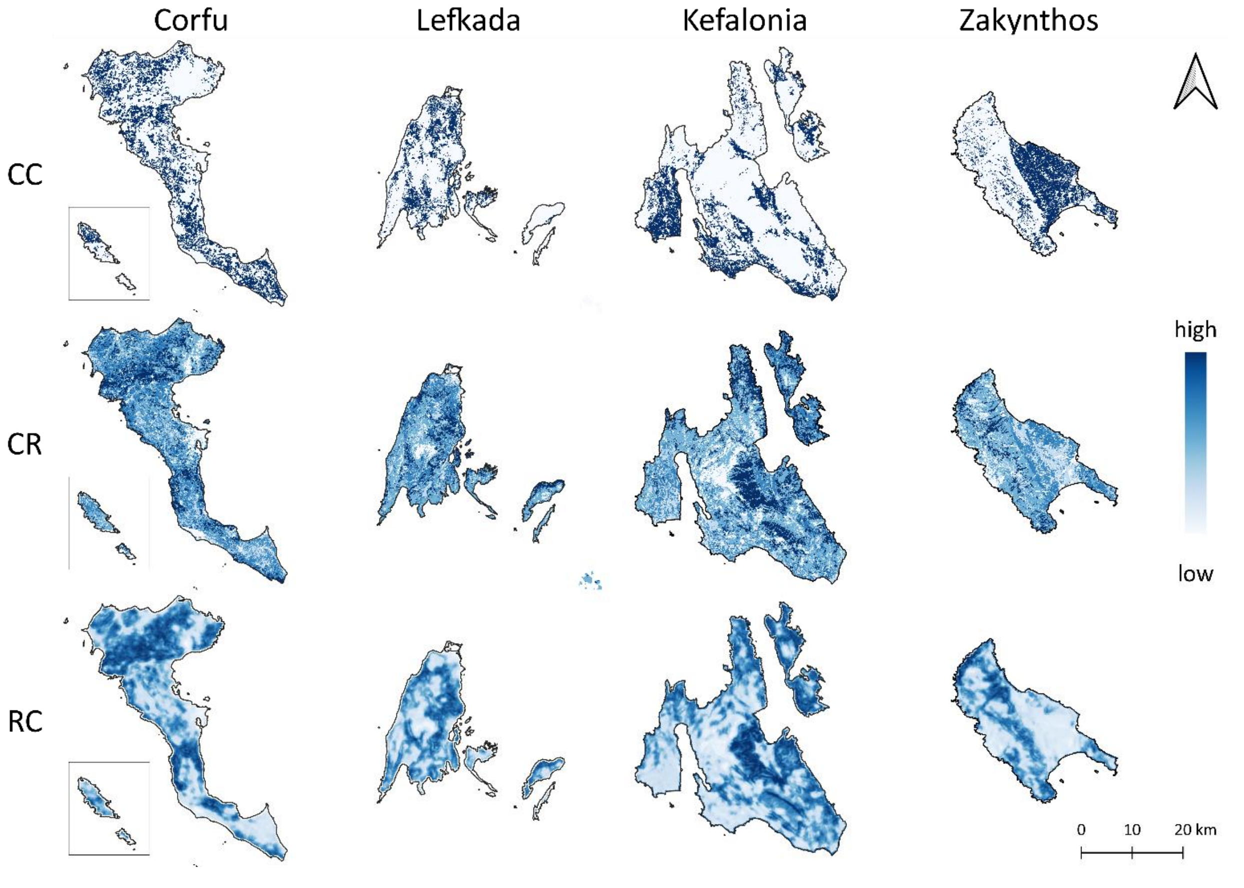


Figure 4.2: ES supply maps for 2015; FP: food provision; CR: climate regulation; RC: recreation. Source: adapted from Lorilla et al. (2019).

The presence of olive groves also benefited the supply of climate regulation. In general, the ES supply of climate regulation was provided across the whole study area, with greater intensity appearing in forested and agro-forested mountainous regions. In comparison, urban and rural areas, which are sources of GHG emissions, were characterized by high demand for climate regulation. Compared to the other islands, only the main urban region of Lefkada (located in the north) did not present extremely high demand for this service.

Similarly, high values of recreation supply were found in mountainous, highly vegetated, and, often, remote areas. This result conforms to the distribution of recreation demand, as areas with low accessibility are dominated with high supply. In particular, on Kefalonia and Zakynthos, mountainous regions with large amounts of natural vegetation are not accessible via road and path networks, or are far from settlements. In contrast to the case of Corfu and Lefkada, recreation supply and demand had similar patterns in highly vegetated areas.

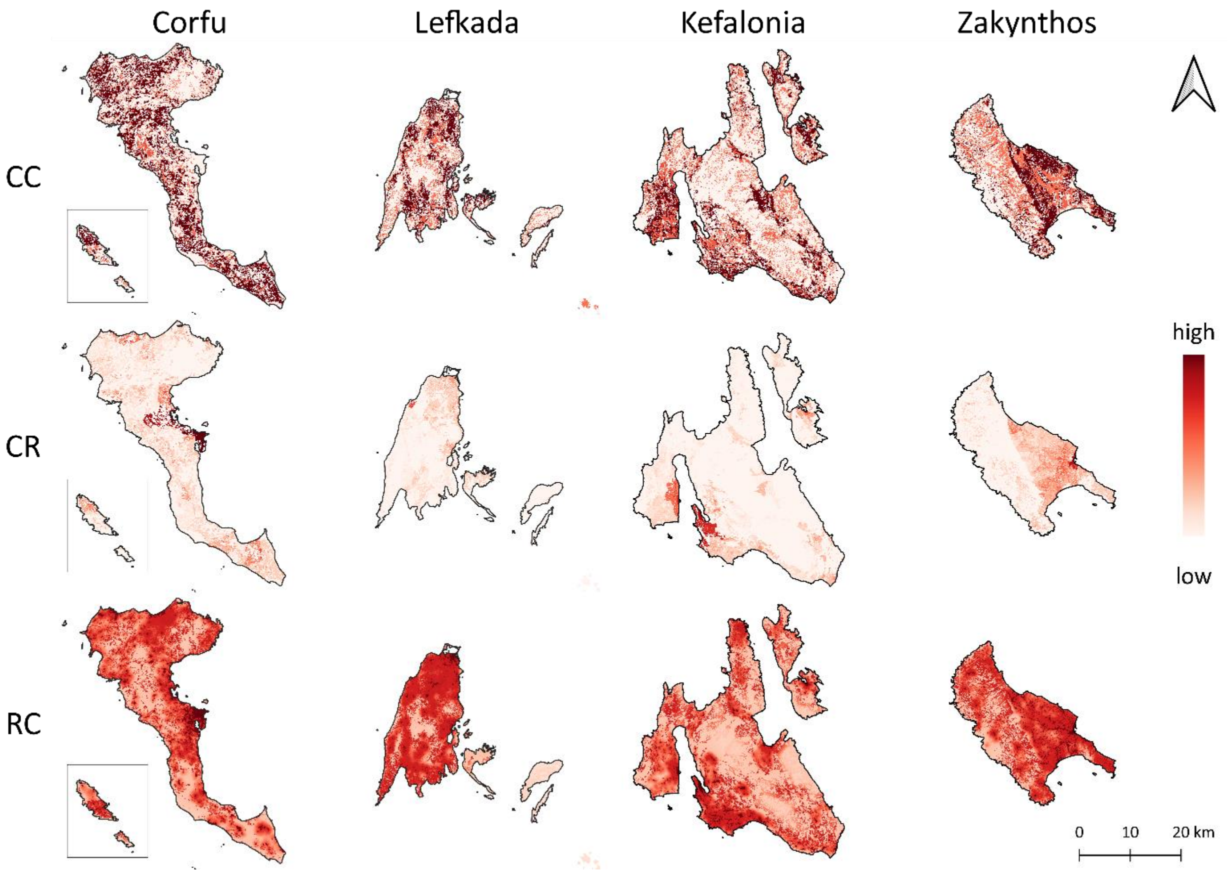


Figure 4.3: ES demand maps for 2015; FP: food provision; CR: climate regulation; RC: recreation. Source: adapted from Lorilla et al. (2019).

4.4.2 Spatial similarities and mismatches of ESs

A clear distinction of regions with higher excess supply or unsatisfied demand was found (Figure 4.4). In general, supply and demand for food provision presented similar patterns, where demand areas entirely overlapped areas with ES supply, especially for Corfu. Excess demand was not found at any location in the entire study area, while excess supply of food provision was more evident on the main island of Zakynthos. The congruence between ES supply and demand was higher for climate regulation compared to the other two services. Excess supply of climate regulation was located in highly natural areas, while excess demand was concentrated around urban, rural, and agricultural regions. In comparison, recreation had large areas of excess supply and demand, as most regions exhibited either high supply or high demand.

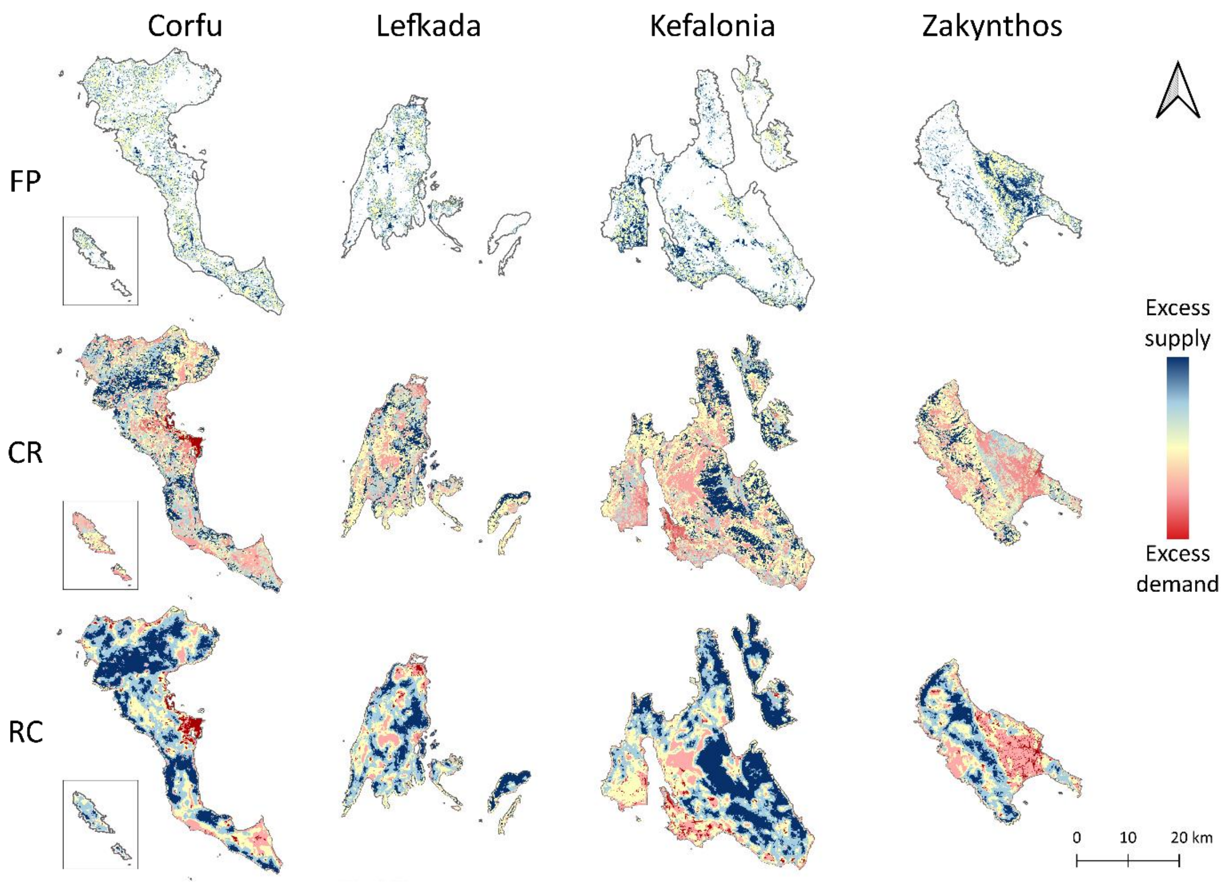


Figure 4.4: Spatial matches and mismatches between the supply and demand of ES. Source: adapted from Lorilla et al. (2019); Blue spaces are classified as high ES supply (possibly under an excess supply regime), red spaces are classified as high ES demand (possibly under unsustainable use regime), and yellow areas are the spatial match between ES supply and demand (balanced situation); FP: food provision; CR: climate regulation; RC: recreation; white areas in the FP service refer to non-existent supply and demand.

4.5 Results on the ES hot and coldspots

4.5.1 Zones of excess supply and demand of ESs

The spatial patterns of hot spots and cold spots were distinct (Figure 4.5). The results revealed discrepancies between the distributions of hot spots of food provision, climate regulation, and recreation, especially on the islands of Lefkada, Kefalonia, and Zakynthos, where hot spots of food provision were both cold spots of climate regulation and recreation, and vice versa at the same time. The most evident region for all three ES was zone 3, which possibly had a balanced state between supply and demand, followed by zone 1, with excess supply, and zone 5 with excess demand. A small number of hexagons constituted zones 2 and 4.

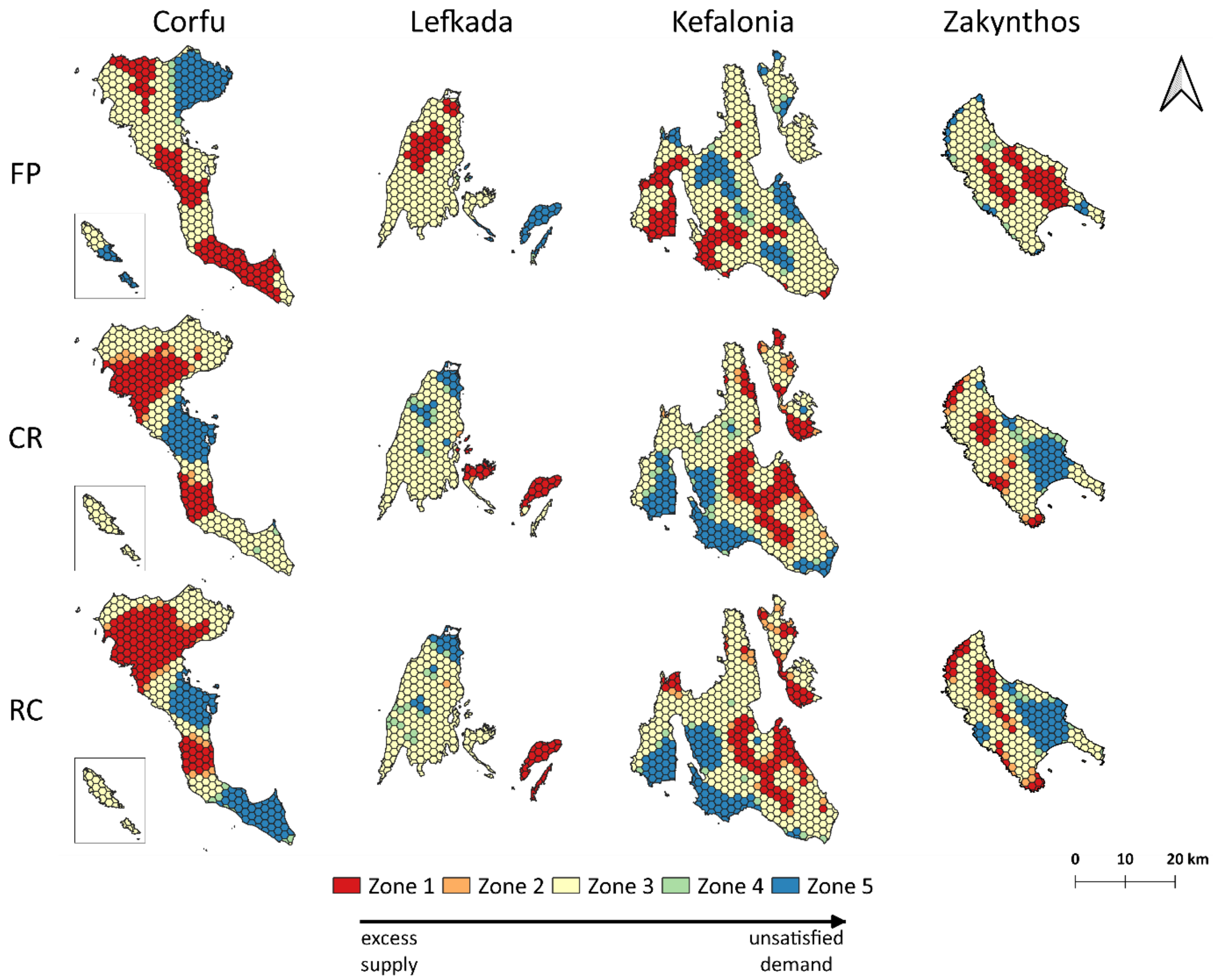


Figure 4.5: ES flow zones identified by hot spot analysis (z-values results classified in 5 zones). Source: adapted from Lorilla et al. (2019); FP: food provision; CR: climate regulation; RC: recreation.

The hot and cold spot maps, as well as their degree of significance (Figure 4.6), showed that all islands mostly contained hot spots of food provision, except for Kefalonia and the northern mountainous part of Corfu, where zones of significantly unsatisfied demand were noticeably present. Zones of excess supply of climate regulation and recreation were distributed in areas of high naturalness, while rural, urban, and the agricultural regions with flatter relief exhibited unsatisfied demand. Hence, hot and cold spots of climate regulation, along with recreation, had similar distributions, but differed to that of food provision.

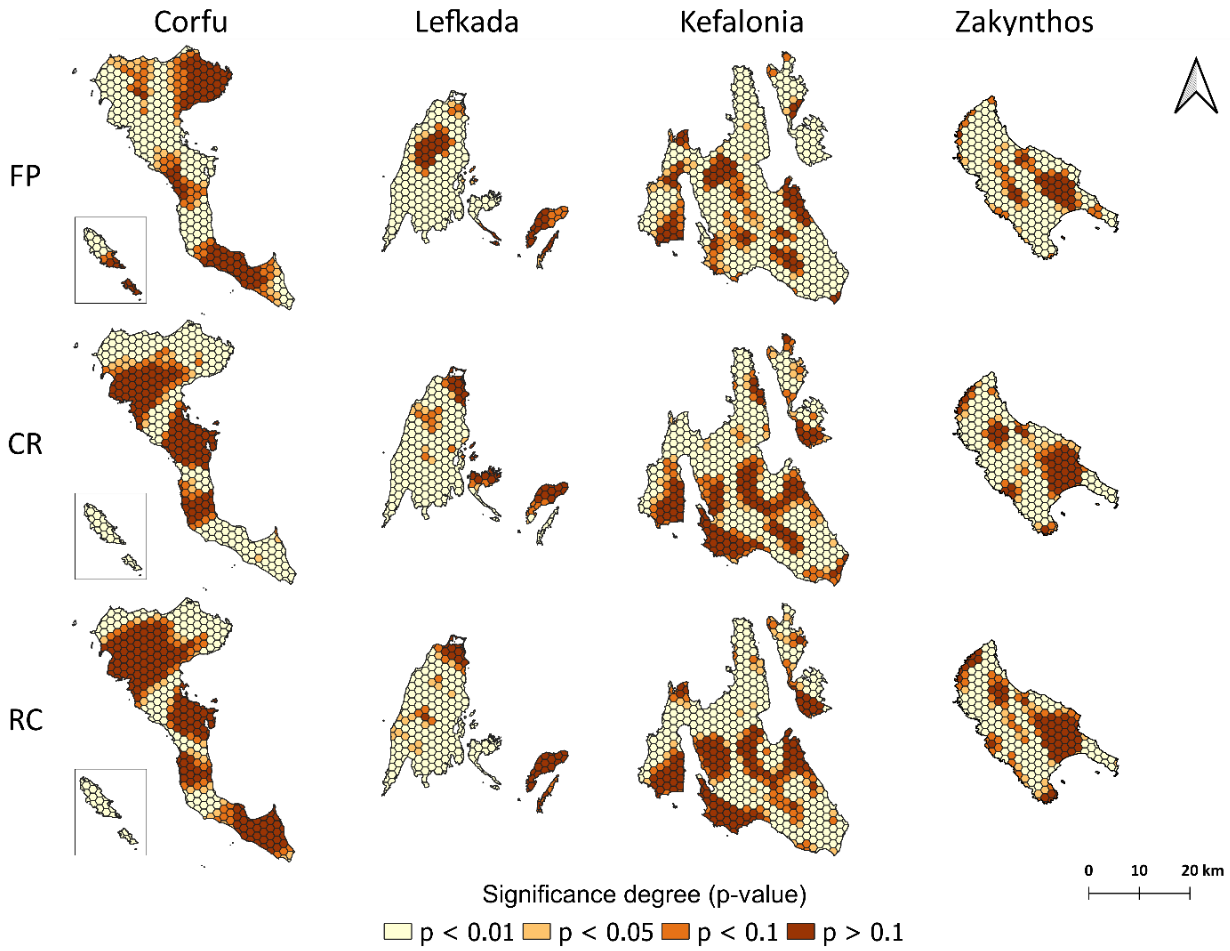


Figure 4.6: ES flow zones identified by hot spot analysis (p-values results). Source: adapted from Lorilla et al. (2019); FP: food provision; CR: climate regulation; RC: recreation.

Across the ES flow zones, as well as within each zone, distinct patterns regarding the differences between the magnitudes of ES supply and demand were found (Figure 4.5 and Table 4.4). Supply and demand for food provision significantly differed among zones based on one-way ANOVA (Table 4.4 and 4.5). Specifically, the supply of food provision in zone 1 was significantly lower than that in zones 3 and 5, showing a gradient from low to high ES values (Table 4.6). Similar results were obtained for the demand for food provision, with zone 1 (hot spots) presenting significantly lower values compared to zone 3 (balanced zone) [Table 4.7].

Table 4.4: Mean ES values for each zone and one-way ANOVA results among ES zones. Source: adapted from Lorilla et al. (2019); ESS: ES supply, ESD: ES demand.

	FOOD PROVISION		**CLIMATE REGULATION**		**RECREATION**	
	ESS	**ESD**	**ESS**	**ESD**	**ESS**	**ESD**
ZONE 1	0.45	0.43	0.73	0.41	0.81	0.27
ZONE 2	0.49	0.49	0.62	0.42	0.77	0.29
ZONE 3	0.58	0.53	0.42	0.47	0.60	0.30
ZONE 4	0.60	0.50	0.35	0.53	0.34	0.32
ZONE 5	0.63	0.56	0.33	0.59	0.37	0.39
ANOVA F(4,1518) =	8.74***	5.21***	227.00***	35.31***	126.00***	67.95***

*** p < 0.001, ** p < 0.01, * p < 0.05

Table 4.5: Results of the post-hoc test identifying statistically significant differences between ESS and ESD within each ES zone. Source: adapted from Lorilla et al. (2019).

	FOOD PROVISION		**CLIMATE REGULATION**		**RECREATION**	
	mean diff. (ESS-ESD)	**p-values**	**mean diff. (ESS-ESD)**	**p-values**	**mean diff. (ESS-ESD)**	**p-values**
ZONE 1	-0.05	0.049	0.39	<0.001	0.51	<0.001
ZONE 2	-0.04	0.338	0.26	<0.001	0.45	<0.001
ZONE 3	0	0.919	0.01	0.097	0.22	<0.001
ZONE 4	-0.01	0.844	-0.1	0.015	-0.05	0.100
ZONE 5	0.02	0.608	-0.28	<0.001	-0.06	0.003

Table 4.6: Post-hoc comparisons using Games-Howell Post hoc test. Source: adapted from Lorilla et al. (2019); numbers refer to mean difference in ES supply of food provision between zones.

	ZONE 1	**ZONE 2**	**ZONE 3**	**ZONE 4**	**ZONE 5**
ZONE 1	-	-0.01	-0.12***	-0.08	-0.14***
ZONE 2		-	-0.11*	-0.06	-0.12
ZONE 3			-	0.04	-0.02
ZONE 4				-	-0.06
ZONE 5					-

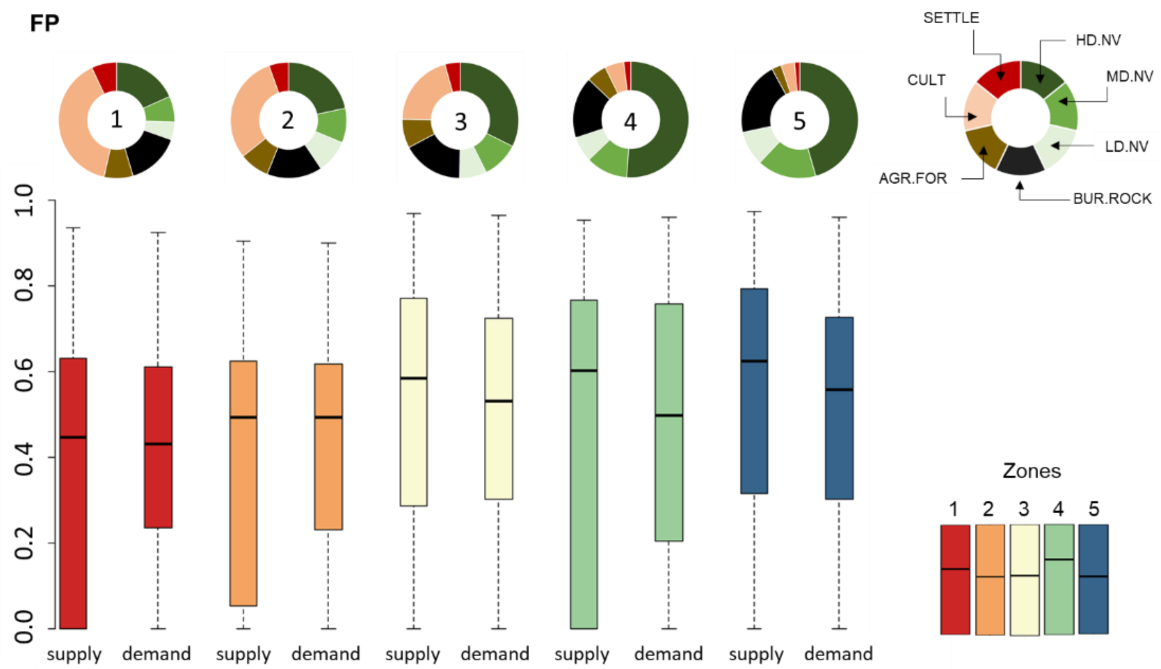
*** p < 0.001, ** p < 0.01, * p < 0.05

Table 4.7: Post-hoc comparisons using Games-Howell Post hoc test. Source: adapted from Lorilla et al. (2019); numbers refer to mean difference of ES demand for food provision between zones.

	ZONE 1	**ZONE 2**	**ZONE 3**	**ZONE 4**	**ZONE 5**
ZONE 1	-	-0.01	-0.08***	-0.04	-0.07
ZONE 2		-	-0.07	-0.03	-0.06
ZONE 3			-	0.03	0.00
ZONE 4				-	-0.03
ZONE 5					-

*** p < 0.001, ** p < 0.01, * p < 0.05

Within each zone for food provision, ES supply exhibited similar values to demand, with supply showing a bigger variation in values (Figure 4.7). Thus, for the most part, demand for food provision was met. Zone 1 (representing excess supply of food provision) was characterized by the high presence of croplands, while zone 5 (representing excess demand) was dominated by forests and shrublands, followed by open areas and transitional vegetation (Figure 4.7).



Graph 4.1: Differences between supply and demand for food provision within ES flow zones. Source: adapted from Lorilla et al. (2019).

In contrast to the similarity between the supply and demand for food provision, the hot spots for climate regulation (zones 1 and 2) had significantly higher supply than demand (Table 4.4 and 4.5). In comparison, significantly higher demand in relation to ES supply was found in the cold spot regions (zones 4 and 5). Subsequently, the gradient from zone 1 to zone 5 exhibited a gradient from higher to significantly lower ES supply values, as well as a gradient from lower to significantly higher ES demand values (Tables 4.8 and 4.9).

Table 4.8: Post-hoc comparisons using Games-Howell Post hoc test. Source: adapted from Lorilla et al. (2019); numbers refer to mean difference of ES supply of climate regulation between zones.

	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5
ZONE 1	-	0.10***	0.28***	0.37***	0.40***
ZONE 2		-	0.18***	0.26***	0.30***
ZONE 3			-	0.09***	0.12***
ZONE 4				-	0.04
ZONE 5					-

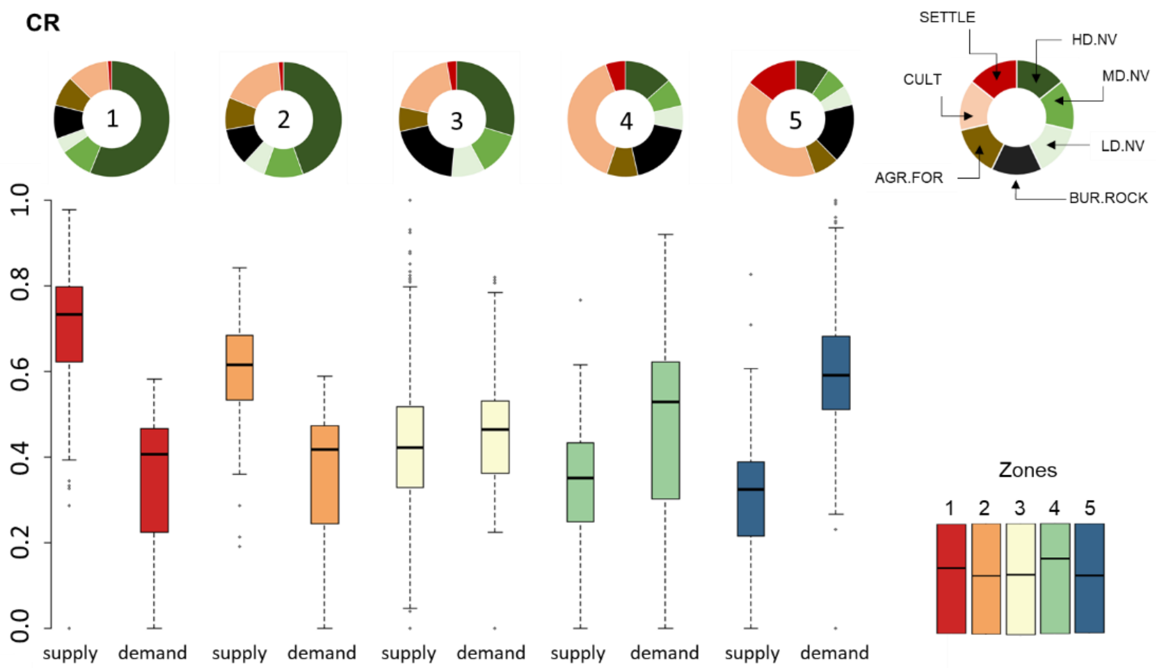
*** p < 0.001, ** p < 0.01, * p < 0.05

Table 4.9: Post-hoc comparisons using Games-Howell Post hoc test. Source: adapted from Lorilla et al. (2019); numbers refer to mean difference of ES demand for climate regulation between zones.

	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5
ZONE 1	-	-0.02	-0.09***	-0.11*	-0.26***
ZONE 2		-	-0.07	-0.09	-0.24***
ZONE 3			-	-0.02	-0.17***
ZONE 4				-	-0.14**
ZONE 5					-

*** p < 0.001, ** p < 0.01, * p < 0.05

In addition, high density vegetation gradually decreased in extent from the hot spot zones to cold spot zones, whereas croplands and settlements gradually increased (Figure 4.8). Zone 3 of both food provision and climate regulation exhibited a balanced state between supply and demand, as well as a similar composition of LULC categories (Figure 4.8).



Graph 4.2: Differences between supply and demand for climate regulation within ES flow zones. Source: adapted from Lorilla et al. (2019).

Similar to climate regulation, the supply of recreation tended to decrease from hot to cold spots, as opposed to the increase in demand for it (Figure 4.9 and Table 4.8). This phenomenon was verified by the results of one-way ANOVA, as statistical differences were found among the zones of both recreation supply and demand (Tables 4.10 and 4.11). Specifically, each zone of recreation supply was significantly lower than the previous zone ($p < 0.001$).

Compared to climate regulation, a different pattern was observed concerning the significant differences between supply and demand among the ES flow zones (Figure 4.9). From zones 1 to

5, the difference between supply and demand significantly decreased until a balanced situation was reached, where cold spots had a similar magnitude for recreation supply and demand (Table 4.4 and 4.5). The composition of LULC categories within the zones was similar to that of the climate regulation service (Figure 4.9).

Table 4.10: Post-hoc comparisons using Games-Howell Post hoc test. Source: adapted from Lorilla et al. (2019); numbers refer to mean difference of ES supply of recreation between zones.

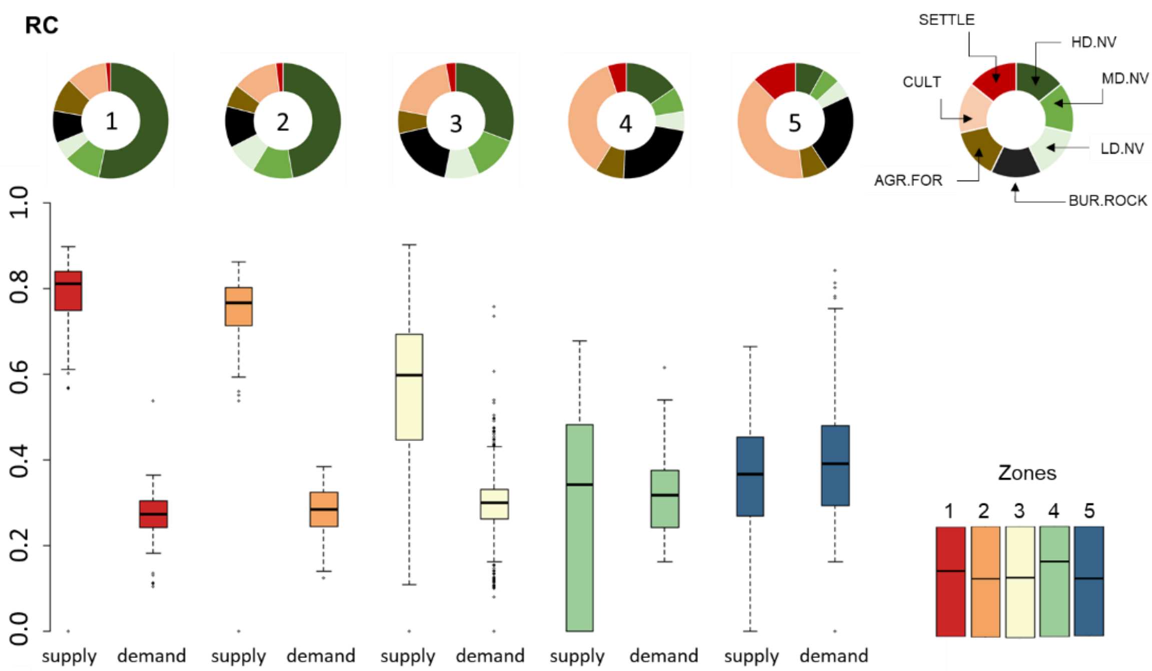
	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5
ZONE 1	-	0.06	0.26***	0.51***	0.43***
ZONE 2		-	0.21***	0.46***	0.38***
ZONE 3			-	0.25***	0.17***
ZONE 4				-	-0.08
ZONE 5					-

*** p < 0.001, ** p < 0.01, * p < 0.05

Table 4.11: Post-hoc comparisons using Games-Howell Post hoc test. Source: adapted from Lorilla et al. (2019); numbers refer to mean difference of ES demand for recreation between zones.

	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5
ZONE 1	-	-0.01	-0.03***	-0.05***	-0.14***
ZONE 2		-	-0.02	-0.04*	-0.13***
ZONE 3			-	-0.02	-0.11***
ZONE 4				-	-0.09***
ZONE 5					-

*** p < 0.001, ** p < 0.01, * p < 0.05



Graph 4.3: Differences between supply and demand for recreation within ES flow zones. Source: adapted from Lorilla et al. (2019).

4.6 Discussion

Understanding the relationship between supply and demand is an important issue when managing ES (Goldenberg et al., 2017). The selection of proxy indicators to map the supply of ES depend on the purpose of the study, the end users, and the availability of data. While the targeted audience is an important criterion when mapping ES, the selected indicators can provide insights and inform a wide range of people involved at the scientific, policy and management sector. Both simple and complex approaches that were used reflect the importance of maintaining healthy ecosystems and the services they provide. Given the diversity and complexity of ES demand, a single valuation method might not had presented a complete perspective; that is because not all economic valuation methods can be applied on all ES. On the other hand, the quantification and mapping of ES demand, based on different methods and typologies, can offer different insights of the ecosystems and the services they provide. This agrees with Wolff et al. (2015), who suggested that a unified conceptualization better reflects the different processes underlying demand for ESs.

To identify ES hot spots, Schröter & Remme (2016) reviewed ES delineation methods through a literature search, demonstrating no clear link between distinct hot spot methods and specific ES policy questions/purposes. Yet, Bagstad et al. (2016) successfully used the Getis-Ord Gi* statistic to match both ES supply and social value hot spots when assessing synergies, trade-offs, and conflicts. In this chapter, ES supply and demand were combined using this hot spot method that generated large clustered areas, connected throughout the landscape. This is preferable as smaller areas could lose a considerable part of their value if neighboring areas are not conserved (Schröter & Remme, 2016). Subsequently, by spatially comparing the patterns of demand and supply, it was able to identify areas where the supply of services and societal demand aligned. Although there remains difficulty in deciding how the ES concept could be used to facilitate decision- and policy- making process (Bennett & Chaplin-Kramer, 2016; Maes et al., 2018a), the combination of both supply and demand for a particular service has proven useful in the design of various environmental agendas (Orta Ortiz & Geneletti, 2018).

4.6.1 Spatial similarities and mismatches between the supply and demand of ESs

The results of spatially analyzing ES mismatches showed that ES supply was not completely aligned with ES demand with respect to their spatial distribution. Urban, rural, and agricultural areas in the Ionian Islands exhibited high societal demand (i.e., high economic values), due to the high and long-term presence of people, along with their needs in such locations, which is in accordance with previous studies (Baró et al., 2015; Beichler et al., 2017). This chapter signified that areas where mismatches occurred, a trade-off relationship between ES supply and ES demand is evident. This implies that, excess ES demand can also inhibit the supply of other ESs, taking into account that high demand for food provisioning services usually involves a decline in the supply of regulating and cultural services.

The exact alignment of supply and demand for food provision, and the appearance of excess supply, demonstrated that societal demand was met. This pattern accounted for a general trend, as provisioning services, are the most important to society (Marques-perez et al., 2014; Martínez-Paz et al., 2019). In the case of providing and demanding a specific type of crop, tree crops (especially olive groves) were far more beneficial compared to other crop types. The potential of olive groves to provide high quality goods (i.e., food) services, as well as multiple ESs, has been highlighted by several studies conducted in other Mediterranean areas (Fernández-Habas et al., 2018; Marchi et al., 2018; Montanaro et al., 2017; Bernués et al., 2015). In addition to olive groves, a mixture of other crop types greatly contributed to the local economy of the Ionian Islands, either by providing goods directly to society or by creating products for tourism purposes (Kefalas et al., 2018). The demand for local and traditional food products has grown in many European countries in recent years (Bernués et al., 2014), with the spatial match between supply and demand for food provision on the Ionian Islands being of considerable importance. Some of the services provided by olive orchards are water and climate regulation, erosion prevention and recreation, which in turn are also associated with other ES.

Supply–Demand mismatches were evident for climate regulation. Regions with high demands for climate regulation rarely had high supply, supporting previous studies on regulating services (Goldenberg et al., 2017; Schulp et al., 2014; Stürck et al., 2014; Sun et al., 2018). This relationship might be attributed to the fact that, in areas with high population density, there is a greater need for climate regulation; however, in parallel, human dominated land uses have a comparatively low regulation capacity. This phenomenon exists because anthropogenic activities in urban and agricultural areas have the highest amounts of air-borne gases, including GHG emissions (Kennedy et al., 2011). However, 52% of the Ionian Islands is covered by natural forests and agroforest ecosystems (Kefalas et al., 2018), which explains the significant amount of areas with excess supply or a balanced supply-demand ratio for climate regulation.

Recreation is associated with the ability of people to access recreational areas (Baró et al., 2016; Goldenberg et al., 2017; Schirpke et al., 2018; Syrbe & Grunewald, 2017; Syrbe & Walz, 2012; Turkelboom et al., 2018; Vallecillo et al., 2019; Wolff et al., 2015). The results showed that areas with demand were far from being aligned with supply areas; thus, highly natural regions are not accessible to society, due to the lack of road or path networks (Paracchini et al., 2014). In particular, for Kefalonia and Zakynthos, the low dispersal of settlements in mountainous and semi-mountainous regions led to limited pressure to construct a dense road network to facilitate accessibility to villages. In addition, as the Ionian Islands as a popular location for summer tourism, they are characterized by seasonal demand for coastal-oriented tourism activities (Martinis et al., 2016), which leaves highly natural and remote areas unaffected by tourism disturbance (Geri et al., 2010). However, regions of high naturalness, where there is a surplus of recreation supply, could be threatened by human interventions (such as frequent fire events). In other Mediterranean areas, these regions might be connected with tourism and economic development (Vogiatzakis et al., 2008). In contrast, the scarcity of available green spaces in urban areas limits the potential for outdoor recreation (Hartter, 2010; Daniel et al., 2012; Baró et al., 2016; Orta Ortiz and Geneletti, 2018), leading to mismatches between the supply and demand for urban recreational activities, along with other ESs that also depend on the landscape's naturalness.

Information on the matches and mismatches of ES could facilitate more efficient spatial planning and the identification of priority areas for conservation. Focusing on just the potential supply of ESs, without understanding how it correlated with society demands, could lead to misleading information on important questions about where benefits are limited to beneficiaries. The framework followed in this chapter allowed to delineate the spatial linkage between the supply and demand of three ecosystem services, and to identify zones where excess supply and demand exist. The findings herein show that the Ionian Islands have a surplus of ES supply in highly natural areas, but that excess societal demand for services is concentrated in urban areas. Furthermore, this chapter showed that the identification of ES supply and demand hot spots and cold spots could be used to guide the establishment of conservation priorities, because it helped create zones with high connectivity and compactness. Thus, in zones where unsustainable flow exists, suggestions on how to maintain or shift the current state in the future are possible to be made.

CHAPTER FIVE

5 SOCIO-ECOLOGICAL FACTORS AS DETERMINANTS OF ECOSYSTEM SERVICE BUNDLES[5]

"A methodological approach that considers a diverse range of methods to analyze ES associations, and uncovers the ecological and socio-economic factors driving ES bundles may be the only way to deal with the complexity of ES dynamics in socio-ecological systems."

- Mouchet et al. (2014), Global Environmental Change

5.1 Contextual background

The capacity of ecosystems to provide specific ecosystem services (ESs) depends on the interactions between biophysical characteristics and human presence (Gonzalez-ollauri & Mickovski, 2017; Reyers et al., 2013). However, human demand, as expressed by their activities, often creates antagonistic relationships in the supply of multiple ESs. Furthermore, a drop in the provision of ESs might contribute to biodiversity loss and the degradation of ecological quality, and vice versa, threatening human well-being (Lyu et al., 2018). Understanding how different social and ecological factors shape the delivery of ESs is important to achieve effective landscape policy and management. Consequently, identifying the importance of various social and ecological drivers for ESs, especially across different landscapes, has been gaining increasing attention (Dittrich et al., 2017a; Lyu et al., 2019a; Meacham et al., 2016; Schirpke et al., 2019a; Spake et al., 2017). Mediterranean islands are widely recognized as biodiversity hotspots that have a long history of human activities shaping their multi-functional landscapes (Balzan et al., 2018b; Martín-lópez et al., 2016; Vogiatzakis et al., 2016). Socio-economic and environmental factors are among the most important factors driving the creation of these diverse landscapes (Geri et al., 2010; Kefalas et al., 2019; Petanidou et al., 2008). However, socio-economic and environmental factors, along with climate change, might have irreversible consequences on local ecosystems (Kefalas et al., 2018). In this context, this chapter aimed to identify coherent groups of ES supply and demand at the landscape scale, and determine how different drivers influence the spatial distribution of ES bundles in the Ionian Islands.

[5] Parts of this chapter have been published in the form of a scientific article. Citation: Lorilla, R.S., Poirazidis, K., Kalogirou, S., Detsis, V., & Chalkias, C. (2020). Socio-ecological factors as determinants of ecosystem services bundles. Ecological Modelling, 422C, 108994.

5.2 Methodology for identifying predictor variables of ESs

5.2.1 Data preparation

This chapter focused on six ESs, including three provisioning services (Food provision – FP, Livestock provision – LP, Plant-based resources – PR), two regulating and maintenance services (Climate regulation – CR, Maintenance of Nursery Populations & Habitats – NS), and one cultural service (Recreation – RC). Information on ES supply and demand were produced in Chapters 3 and 4. In this Chapter, LP (supply and demand), PR (demand), and NS (demand) were added, to provide six ES supply and six ES demand indicators. Table 5.1 provides an overview of all the indicators that were used to map supply and demand of the selected services.

Table 5.1: Indicators/Proxies used to map the estimated ES. Source: adapted from Lorilla et al. (2020).

ES SECTION	ES	CODE	COMPONENT	INDICATOR/PROXY
PROVISIONING SERVICES	Food provision	FP	Supply	Percentage of cultivated crops[1]
			Demand	Economic value of agricultural products[2]
	Livestock provision	LP	Supply	Percentage of grazing grasslands[3]
			Demand	Livestock animals[4]
	Plant-based resources	PR	Supply	Enhanced Vegetation Index (EVI)[5]
			Demand	Plant biomass usage for heating purposes[6]
REGULATING AND MAINTENANCE SERVICES	Climate regulation	CR	Supply	Below and above ground carbon storage[7]
			Demand	Carbon emissions[8]
	Maintenance of Nursery Populations and Habitats	NS	Supply	Shannon Diversity Index (SHDI)[9]
			Demand	Percentage of protected areas[10]
CULTURAL SERVICE	Recreation	RC	Supply	Recreation potential[11]
			Demand	Economic value of ecosystem types to provide recreation[12]

[1] Percentage of land under cultivation (Lorilla et al., 2018) using agricultural LULC datasets (Kefalas et al., 2018).

[2] Mean annual price of representative agricultural products (Lorilla et al., 2019) using the look-up tables of prices for selected representative products of the EU (European Commission, 2019a, 2019b).

[3] Percentage of land used for grazing purposes based on LULC datasets (Kefalas et al., 2018).

[4] Total number of livestock animals, including cattle, goats, sheep, and pigs (Hellenic Statistical Authority, 2014).

[5] Capacity of ecosystems for energy production (Lorilla et al., 2018).

[6] Percentage of households using plant resources (biomass) as their main energy source for heating purposes (Hellenic Statistical Authority, 2014).

[7] Capacity of vegetation to contribute towards mitigating climate change (Lorilla et al., 2018).

[8] Greenhouse gas emissions per capita (Lorilla et al. 2019).

[9] Diversity of LULC types using Landscape metrics (Lorilla et al., 2018).

[10] Percentage of land under protection policy, including National Parks, Natura 2000, Wildlife refuge (also known as Nature Reserve), and other International Environmental Treaties (Open geospatial data and services of Greece- http://geodata.gov.gr).

[11] Biophysical model of recreation opportunity (Lorilla et al., 2018).

[12] Benefit value of LULC classes to provide recreation services (Lorilla et al. 2019).

Agricultural activities including both crops and livestock production contribute to the livelihoods of rural populations, providing income and to some extent covering household needs. In this sense, food provisioning services in the context of reliance on the agricultural sector play a crucial role in the rural economy of small islands (Balzan et al., 2018a). Climate regulation can support the provision of natural resources and, therefore, ensure the delivery of other essential services. Although the relevant mechanisms operate at much higher geographic scales it is a matter of high importance throughout the globe and carbon sequestration is a process that can be meaningfully assessed at various scales. Recreation in the form of eco-tourism depends on the highly valued - by tourists and locals – naturalness of landscapes. Census data reveal that rural communities of the Ionian Islands use biomass as their main source of heating purposes. However, insufficient management of timber extraction may reduce forest diversity, which in turn, risk the integrity of ecosystem functioning. Finally, the Ionian Islands encompass 14 protected areas included in the Natura 2000 Network, while intense human pressure may negatively affect the ability of sensitive ecosystems to maintain nursery populations and habitats. The significance of Mediterranean islands as biodiversity hotspots also greatly exceeds their geographical borders.

For LP, grazing land cover types were used as the supply indicator and livestock animals as the demand indicator, assuming that the number of reared animals could be used to express the demand of society for livestock provision (Syrbe & Grunewald, 2017). Demand for plant-based energy resources was estimated using social data on the percentage of households consuming biomass for heating purposes. The percentage of land under any protection policy was used as the demand indicator of NS, assuming that protected areas have high demand for conservation and maintenance of biodiversity and ESs, which can maintain human well-being (Palomo et al., 2011).

To identify the relationships between ES and socio-ecological factors, all ESs and variables were aggregated to a common spatial unit, as socio-economic censuses were only available at the administrative level [municipal district level given by the Hellenic Statistical Authority (2014);

Figure S11 in Supplementary material]. In specific, the average value of ESs and variables in each municipality was estimated using the R package *spatialEco* version 1.2-0 (Evans & Ram, 2019). The initial dataset included 278 administrative units for the Ionian Islands, from which three municipal districts representing three small islets were excluded from the analysis due to missing ES and socio-ecological data (Figure S11 in the Supplementary material).

5.2.2 Selection and mapping of socio-ecological variables

A critical step before employing any method is the compilation of a list of the most important drivers that may affect different aspects of a socio-economic and ecological system, and that are important to both the explanation and prediction of ES bundles (Marty et al., 2014; Spake et al., 2017). This selection is mainly based on associations between ES and different factors that have been determined by previous literature or expert knowledge. Therefore, based on the published literature, 17 predictor variables (Table 5.2) related to human influence, environmental parameters, and landscape structure were selected.

The demographic (*Population density*, *Employment rate*) and artificial infrastructure variables (*Hotel density*, *Factory density* and *Road density*) were selected for their influence on ecological degradation as a result of socioeconomic and urban development (Meacham et al., 2016). Human population growth has been associated with substantial land use changes, which, in turn, directly affect the supply of ESs. Also, along with population growth, increasing employment rates is an index of economic activity, which is associated both with enhanced material flows. Infrastructure development (such as touristic accommodations and roads) place high pressure on ecosystems by taking up space through sealing thus inhibiting ecosystem functions and generating high demand for food, water supply, water usage, and wastewater discharges (Kefalas et al., 2019; Pinto et al., 2013; Plieninger et al., 2016).

Climate conditions directly affect natural ecosystems and the services they provide, impacting human well-being. Key climatic parameters that affect ecological systems include annual mean *Temperature* and *Precipitation* (Nelson et al., 2006). The selection of topographic factors (*Elevation*, *Slope*) was supported by the assumption that the isolation and accessibility of land constrain the distribution of human activities and their impact on local ecosystems (Kefalas et al., 2019; Meacham et al., 2016). Along with aforementioned variables, *aspect* constitutes a key topographic feature that affects soil and microclimate, which, in turn, influence the composition of vegetation, and therefore, determines the supply of ESs (Bennie et al., 2006; Yapp et al., 2010; Zhu et al., 2019).

Landscape structure and configuration, resulting from complex interactions between biotic and abiotic factors, as well as land use choices made by society, have a significant influence on the supply of ESs and, hence, on human well-being (Herrero-Jáuregui et al., 2019; Mitchell et al., 2015). In this study, metrics of fragmentation (NP, DIVISION), connectivity (PD, CONTAG, IJI), and heterogeneity (SHDI, PR) were estimated at the landscape level. Landscape fragmentation has shown negative effects on ES supply, whilst landscape connectivity is expected to substantially influence the provision of ES (Mitchell et al., 2015; Mitchell, 2013). In parallel, understanding the relationships between landscape heterogeneity and the provisioning of ES within different landscapes is critical for future land management (Turner et al., 2013). This aspect is particularly important for Mediterranean landscapes that are highly mosaic in nature due both to rugged terrain and historical land use (Detsis et al., 2010; Kefalas et al., 2019).

Table 5.2: List of the variables used to explain and predict the distribution of ES bundles. Source: adapted from Lorilla et al. (2020).

CATEGORY	DRIVER	DESCRIPTION
DEMOGRAPHY	Population[1]	Number of inhabitants per hectare
	Employment[1]	Employment rate
ARTIFICIAL AND URBAN STRUCTURES	Hotels[1]	Number of hotels per hectare
	Factories[1]	Number of buildings under industrial use per hectare
	Roads[2]	Road length (km) per hectare
CLIMATE	Temperature[3]	Mean temperature (^oC)
	Precipitation[3]	Mean precipitation (mm)
TOPOGRAPHY	Elevation[4]	Mean elevation (m)
	Slope[4]	Mean slope value (degrees)
	Aspect[4]	Majority of direction of slope face

[1] Hellenic Statistical Authority (2014)

[2] OpenStreetMap Contributors (2018); note, all categories of the Open Street Dataset were used in the analysis.

[3] Worldclim—global climate data (https://www.worldclim.org/)

[4] National Aeronautics and Space Administration – ASTER GDEM 30 m (https://search.earthdata.nasa.gov)

Table 5.2: (Continued).

CATEGORY	DRIVER	DESCRIPTION
LANDSCAPE STRUCTURE[5]	Number of Patches (NP)	Total number of patches per municipal district
	Patch Density (PD)	Patch density per municipal district
	Contagion Index (CONTAG)	Extent to which patch types are aggregated or clumped as a percentage of the maximum possible
	Interspersion and juxtaposition index (IJI)	Extent to which patch types are interspersed as a percentage of the maximum possible
	Landscape division index (DIVISION)	Probability that two randomly chosen places in a municipality are not situated in the same patch
	Patch richness (PR)	Number of different patch types present per municipal district
	Shannon diversity index (SHDI)	Amount of patch type per municipal district

[5] Datasets consisted of LULC for 2015 (Kefalas et al., 2018). The descriptions of Landscape metrics were adapted from the help contents of the Fragstats software version 4.2.1 (McGarigal et al., 2012).

5.2.3 Identifying bundles and predictor variables of ESs

Each ES map was standardized to a scale between 0 and 1, based on the minimum and maximum values; higher values correspond to greater magnitude of services. The framework for identifying predictor variables and their importance in forming ES bundles consisted of two main parts: the bundle identification framework, and the Random Forest (RF) model (Figure 5.1).

Following the methodology of Chapter 3, the bundle identification framework was used to distinguish bundles of ES supply and demand. First, Spearman correlation tests were performed on pairs of ES supply and ES demand to reveal the relationship among all services. The strength of the relationship was determined using correlation coefficients, which were classified into three levels (Cui et al., 2019): strong relationship ($|\rho| > 0.5$), moderate relationship ($0.5 > |\rho| \geq 0.3$), and week relationship ($|\rho| < 0.3$). Second, Principal Component Analysis (PCA) was performed to identify ES variability explained by the PC axes. The two analyses were used to evaluate the relationships among ES in terms of synergies and trade-offs at the landscape level. Third, Ward's hierarchical clustering method, using Euclidean distance as the measure of proximity, was used to create sets of ESs that spatially overlapped in a certain way within a given area, i.e., ES bundles. The optimal number of clusters was determined by the Silhouette method, which computes the average silhouette of observations for different values of clusters (Kaufman & Rousseeuw, 2008). This measure delineated five optimal clusters for ES supply and six optimal clusters for demand. The categorization of the study area in ES bundles was used as the dependent variable in the RF models.

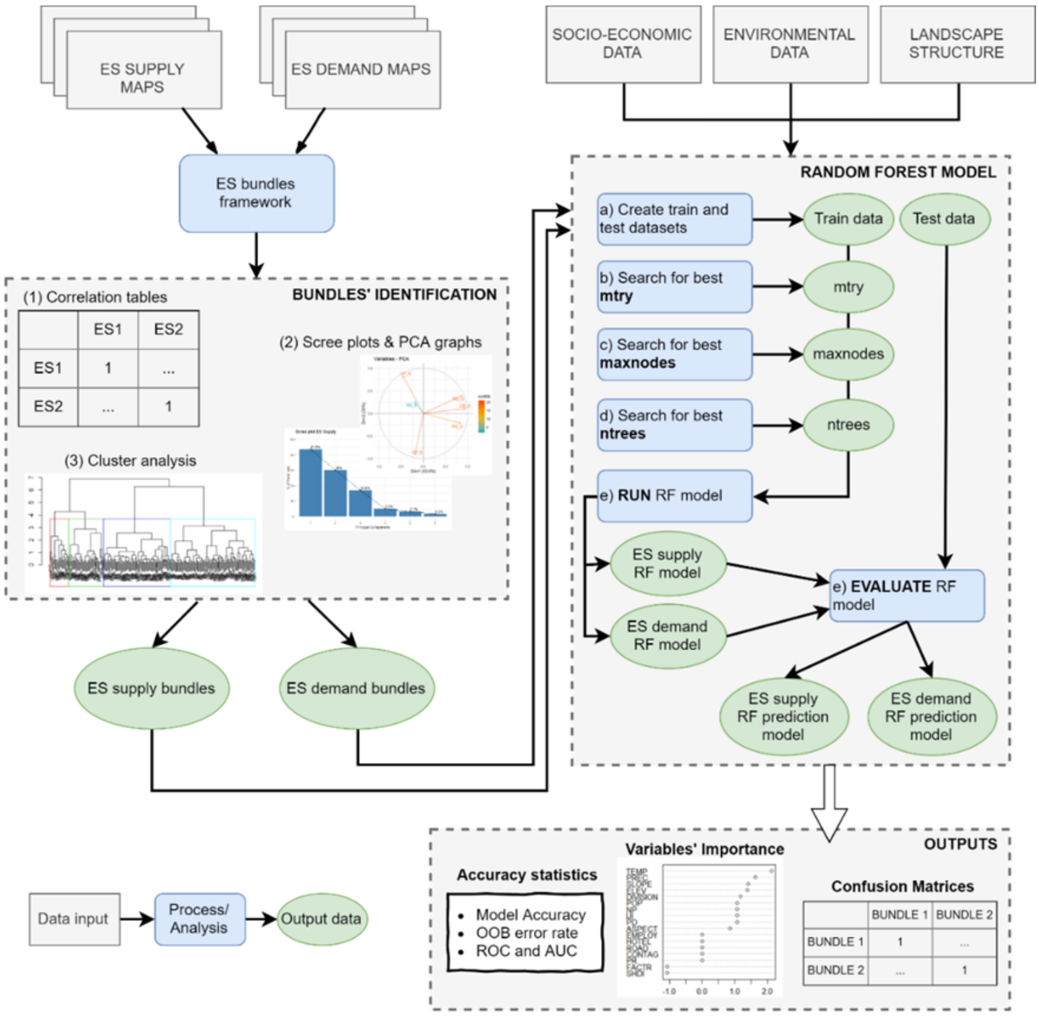


Figure 5.1: Methodological framework to identify important socio-ecological factors that contribute to the distribution of ES bundles. Source: adapted from Lorilla et al. (2020).

Because this chapter aimed to explain the distribution of five and six ES bundles (i.e., categorical data), the classification RF model was employed over the regression RF model, which can only be applied to continuous data. A random forest is "a classifier consisting of a collection of tree-structured classifiers $\{h(x, \Theta_k), k = 1, \dots\}$ where the Θ_k are independent identically distributed random vectors and each tree casts a unit vote for the most popular class at input x" (definition from Breiman 2001). When employing an RF model, the first step involves creating training sets, called bootstraps, from a random resampling of the original dataset. Observations of the original dataset that do not occur in a bootstrap sample are called out-of-bag (OOB) observations (Cutler et al., 2007). Thus, the training dataset was created from 70% of randomly selected samples of the initial dataset (184 municipalities), while the remaining 30% consisted of the test dataset (91 municipalities). The RF algorithm consists of the main model and the prediction model. The main

RF model was applied to the training dataset and was used to identify the importance of predictor variables in the classification of the study area in specific bundles. The prediction model was applied using the results of the main RF model to evaluate the accuracy of using socio-ecological variables to predict ES bundles in the test dataset.

The second step is to prepare the RF model properly. When building RF, there are three tuning parameters of interest (Catucci & Scardi, 2020): (1) the number of randomly selected predictors at each tree (***mtry***), (2) the minimum number of records contained in leaf to stop splitting (***nodesize***), (3) and the number of trees (***ntrees***). Careful tuning of these parameters can prevent extended computations with little gain in error reduction (Segal, 2003). Breiman (2001) showed that by setting the *nodesize* parameter to 1, the model produces good accuracy. For the two other parameters (*mtry* and *ntrees*), different values were tested, and the ones with the highest accuracy were selected as more appropriate for use in the RF model (Table 5.3).

Table 5.3: Accuracy tests to select the appropriate values of trees (ntrees), and predictors sampled at each tree (mtry) for the Random Forest models. Source: adapted from Lorilla et al. (2020); when multiple values of ntrees showed the same level of accuracy, the one with the highest multi-class area under the curve was chosen.

	SUPPLY		*DEMAND*			*SUPPLY*		*DEMAND*	
mtry	Accuracy	Kappa	Accuracy	Kappa	**ntrees**	Accuracy	Kappa	Accuracy	Kappa
1	0,627	0,508	0,528	0,286	**50**	0,789	0,729	0,737	0,615
2	0,614	0,495	0,567	0,354	**100**	0,789	0,723	0,706	0,564
3	0,636	0,523	0,551	0,335	**150**	0,778	0,719	0,706	0,564
4	0,615	0,497	0,540	0,320	**200**	0,824	0,773	0,706	0,564
5	0,639	0,531	0,548	0,335	**250**	0,824	0,773	0,706	0,564
6	0,627	0,517	0,545	0,331	**300**	0,824	0,773	0,706	0,564
7	0,634	0,526	0,535	0,320	**350**	0,824	0,773	0,737	0,620
8	0,633	0,524	0,539	0,325	**400**	0,824	0,773	0,737	0,620
9	0,647	0,544	0,546	0,340	**450**	0,824	0,773	0,737	0,620
10	0,638	0,532	0,527	0,309	**500**	0,824	0,773	0,737	0,620
11	0,633	0,526	0,548	0,340	**550**	0,824	0,773	0,737	0,620
12	0,645	0,542	0,537	0,324	**600**	0,833	0,788	0,737	0,620
13	0,631	0,522	0,528	0,311	**800**	0,824	0,773	0,737	0,620
14	0,636	0,530	0,539	0,331	**1000**	0,824	0,773	0,765	0,628
15	0,643	0,540	0,528	0,312	**2000**	0,824	0,773	0,765	0,628
16	0,633	0,526	0,531	0,319					
17	0,628	0,520	0,524	0,308					

Numbers in gray shading indicate values with the highest accuracy, and thus those that were used in the RF models.

The tests were applied separately for the outputs of ES supply bundles and ES demand bundles. Thus, the parameters for the supply RF model differed to those of the demand RF model. Because multiple selections for *ntrees* showed the same level of accuracy, the multi-ROC curve was estimated to select the number of trees. This measure facilitated the selection of the optimal number of trees with the highest ability to distinguish ES bundles.

The third step consists of running the RF model to obtain the OOB error rate and the plot showing variable importance. OOB samples are used to calculate an unbiased error rate, eliminating the need for cross-validation (Prasad et al., 2006). The concept of variable importance is an implicit selection feature performed by RF with a random subspace methodology. It is assessed by the Gini impurity criterion index. The Gini index is a measure of the prediction power of variables in regression or classification, based on the principle of impurity reduction. It is non-parametric and, therefore, does not rely on data belonging to a particular type of distribution. For a given training set T, selecting one case (municipality) at random and allocating it to bundle B_i, the Gini index is written as (Pal, 2005):

$$\boldsymbol{Gini} = \sum \sum_{j \neq i} (f(C_i, T)/|T|)(f(C_j, T)/|T|) \quad [5.1]$$

where $f(C_i, T)/|T|$ is the probability that the selected case belongs to class B_i.

The Gini index should be maximized. Thus, a low Gini (i.e., a greater decrease in Gini) indicates that a particular predictor is more important in separating data into classes. The Gini index can be used to rank the importance of predictor variables for a classification problem.

In Machine Learning, it is essential to measure the performance of a classification problem. While the OOB estimator is commonly considered as an acceptable proxy of the performance of an RF model, for multi – class classification problems, the AUC-ROC (Area Under the Curve-Receiver Operating Characteristics) should be employed as an alternative performance measure (Fawcett, 2006; Hand & Till, 2001; Probst & Boulesteix, 2018). Therefore, the multi-class AUC-ROC was also estimated to reveal the classification capability of the selected variables. ROC is a probability curve, while AUC represents the degree or measure of separability (Equation 5.2).

$$\boldsymbol{AUC} = \int_0^1 ROC(t)dt \quad [5.2]$$

AUC values range from 0.5 to 1.0, where values between 0.50 and 0.70 indicate low model accuracy, between 0.70 and 0.90 indicate moderate model accuracy, and over 0.90 indicate high model accuracy. *"If ROC is a straight line between the (0,0) and (1,1) points of the ROC space*

($AUC = 0.5$), then the constructed binary classification model has no information about the response variable's class and thus prediction is completely random" (Nemes & Hartel, 2010). Therefore, an AUC value of 1.0 indicates a high capability of the model to recognize different classes. In ecological studies, models with an AUC value greater than 0.8 are considered to have good classification accuracy (Humphries et al., 2018).

The final step is to evaluate the RF model and make the prediction. The prediction is applied on the test dataset using the RF model. The outputs of the prediction model are the confusion matrix, which indicates the correctly classified bundles, and the accuracy of the prediction. In addition, the AUC–ROC for each ES bundle was estimated as well.

5.3 Results on the distribution and relationships among ESs at the municipality scale

5.3.1 ES distribution

The spatial distribution of ES for both supply and demand showed variation across the study area and among services (Figures 5.2 and 5.3). In general, the supply of most ES presented different patterns to demand, except for FP and LP, for which supply and demand overlapped spatially. High values of CR and RC supply were evident in mountainous and naturally vegetated regions, while high demand for these services were located in urbanized municipalities. PR and NS did not exhibit any specific patterns. In all cases, higher ES supply extended over large regions, whereas higher ES demand was concentrated in a few municipalities (see demand for LP, PR, NS, and RC in Figure 5.3).

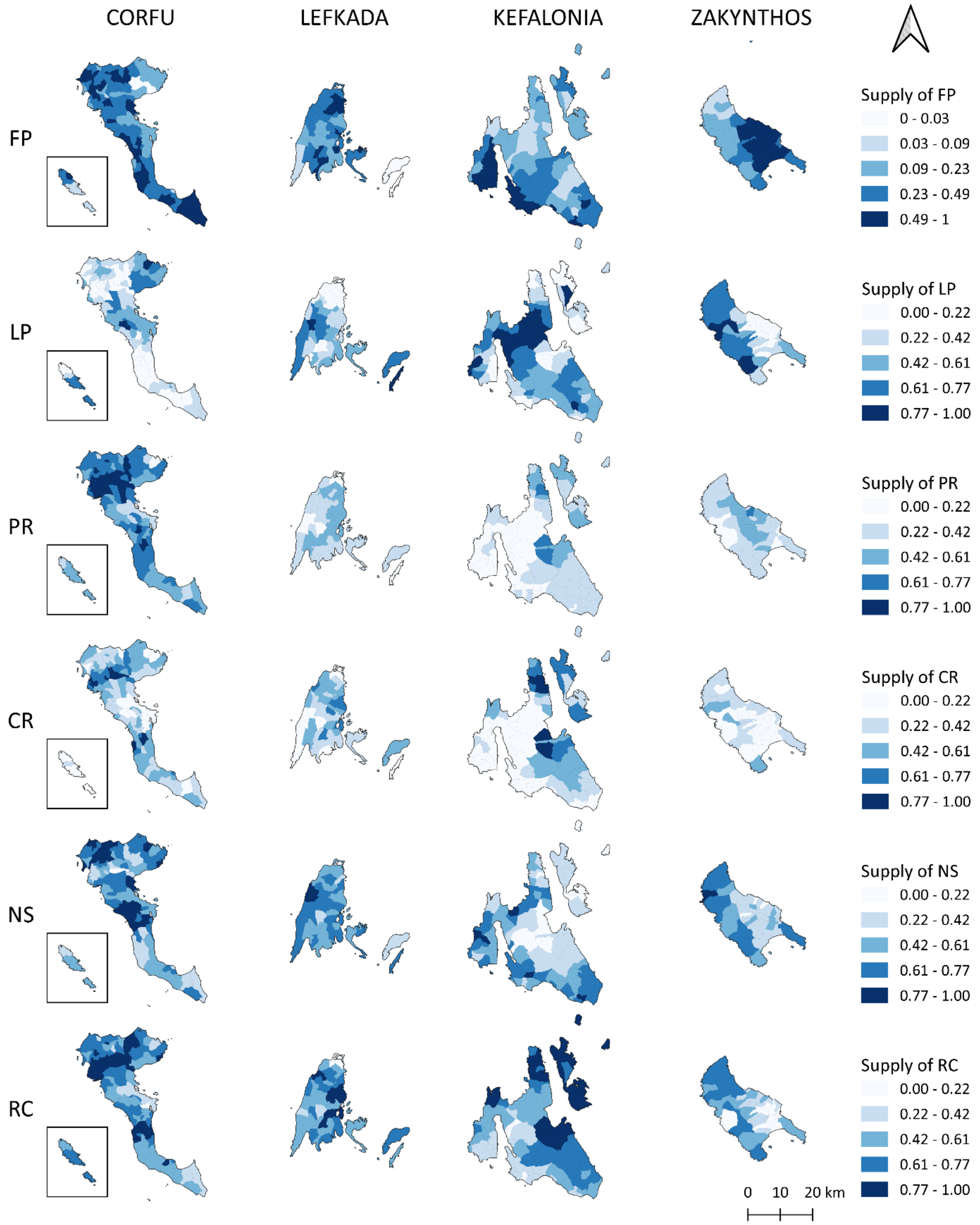


Figure 5.2: Spatial distribution of the standardized ES supply. Source: adapted from Lorilla et al. (2020); FP: food provision; LP: livestock provision; PR: plant-based resources; CR: climate regulation; NS: maintenance of nursery populations and habitats; RC: recreation.

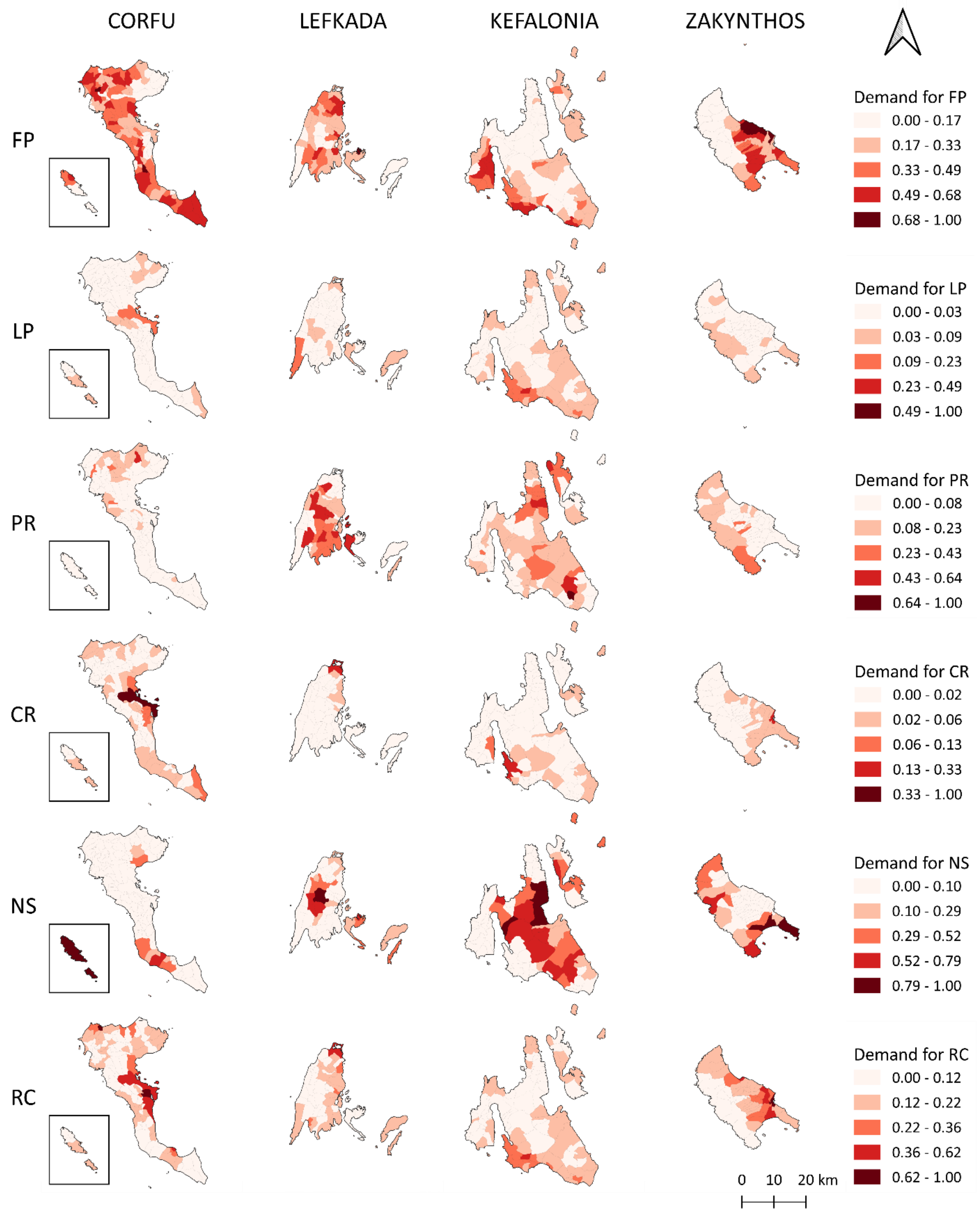


Figure 5.3: Spatial distribution of the standardized ES demand. Source: adapted from Lorilla et al. (2020); FP: food provision; LP: livestock provision; PR: plant-based resources; CR: climate regulation; NS: maintenance of nursery populations and habitats; RC: recreation.

5.3.2 ES relationships

Correlation tests showed variation in the direction and strength of ES relationships (Table 5.4). ES supply pairs had the highest number of strong correlations (four highly correlated pairs). FP and LP mostly had negative relationships, indicating that these services inhibit the presence of other ES. The supply of NS showed non-significant correlations with other ESs from all categories, except for LP, with which it had a moderately positive relationship (r > 0.30). In comparison, RC exhibited significantly strong positive relationships with PR and CR, and a moderately negative relationship with FP.

Table 5.4: Spearman's correlation coefficients for the relationships among supply services (upper left), among demand services (bottom right), and between supply and demand (bottom left). Source: adapted from Lorilla et al. (2020); Strength of correlation: strong relationship (|ρ| > 0.5), moderate relationship (0.5 > |ρ| ≥ 0.3) and week relationship (|ρ| < 0.3). High correlations are in bold font. ES acronyms stand for food provision (FP), livestock provision (LP), plant-based resources (PR), climate regulation (CR), maintenance of nursery populations and habitats (NS) and recreation (RC).

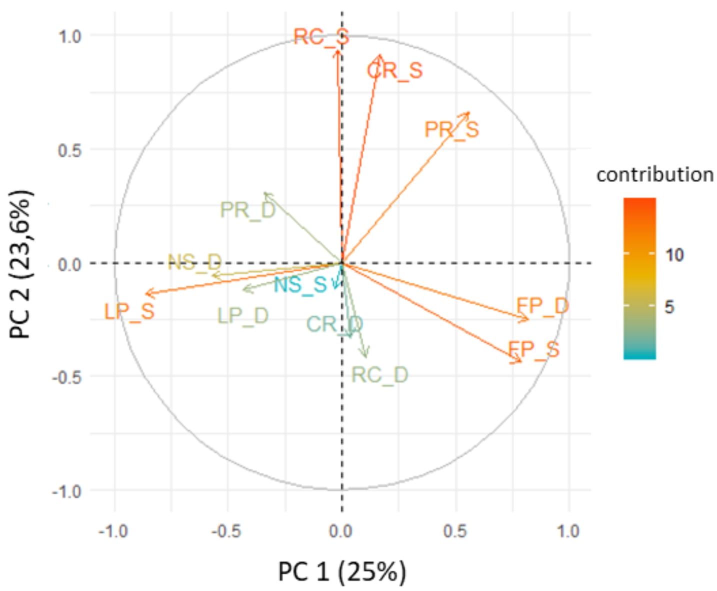
		SUPPLY						**DEMAND**					
		FP	**LP**	**PR**	**CR**	**NS**	**RC**	**FP**	**LP**	**PR**	**CR**	**NS**	**RC**
SUPPLY	**FP**	1											
	LP	**-0,64***	1										
	PR	+0,11	-0,41*	1									
	CR	-0,22*	-0,28*	**+0,66***	1								
	NS	-0,03	+0,31*	0	-0,08	1							
	RC	-0,40*	-0,06	**+0,58***	**+0,87***	+0,03	1						
DEMAND	**FP**	**+0,93***	**-0,64***	+0,23*	-0,05	+0,02	-0,23*	1					
	LP	-0,23*	+0,36*	**-0,53***	-0,25*	-0,1	-0,22*	-0,29*	1				
	PR	-0,17*	+0,15*	-0,19*	+0,17*	-0,03	+0,16*	-0,14*	+0,24*	1			
	CR	+0,31*	-0,24*	+0,14*	-0,2*	-0,03	-0,3*	+0,28*	+0,06	-0,23*	1		
	NS	-0,31*	+0,35*	-0,38*	-0,14*	-0,24*	-0,09	-0,31*	+0,35*	+0,15*	-0,05	1	
	RC	+0,08	-0,16*	0	-0,18*	+0,04	-0,16*	-0,04	-0,1	-0,21*	+0,44*	-0,2*	1

* statistically significant correlations ($p < 0.05$)

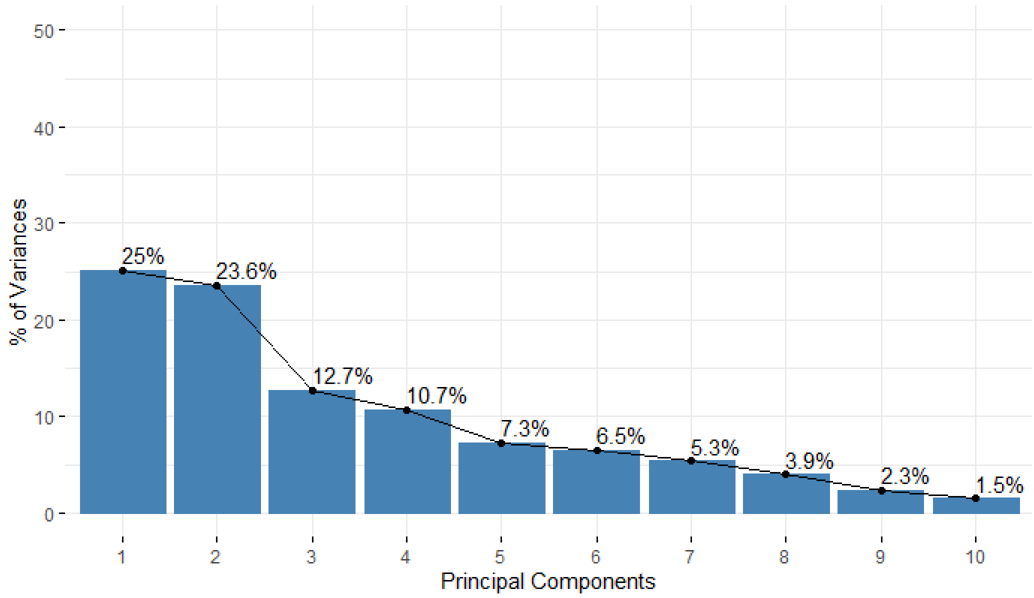
In contrast, only weak and moderate correlations were found in the demand for all ES. The demand for NS (expressed by the amount of protected areas) had negative and positive relationship with the demand for FP and LP, respectively. Unsurprisingly, demand for CR and RC showed a positive relationship, as both demands are related to the presence of people.

Out of the 36 supply-demand ES pairs, 75% were significantly correlated, with 18 low correlated pairs, six moderately correlated pairs, and three highly correlated pairs. The spatial mismatch between the distribution of supply and demand for most ES (PR, CR, NS RC) was also validated by their correlations, which indicated weak negative correlations ($|r| < 0.25$). In comparison, the relationship between supply and demand of FP and LP showed strong ($r = +0.93$) and moderate ($r = +0.36$) positive correlations, respectively. Other strong correlations in supply-demand pairs were those of LP supply-FP demand and PR supply-LP demand, with both pairs having a negative relationship.

Similar results were obtained by the PCA (Graph 5.1). The first two axes explained 49% of total ES variability (Graph 5.2), with two main gradients. The first (horizontal) axis shows gradient from natural vegetation (mostly meadows) to agricultural regions. The former had a supply of LP and demand for NS and LP appeared, while the latter were characterized by both the supply and demand of FP (Table 5.5). In comparison, the second (vertical) axis shows a gradient from urban regions to highly natural areas (mostly forests). The former had a high demands for CR and RC, while the latter was characterized by a high supply of RC, CR, and PR. Beyond the first two axes (PC1 and PC2), PC3 and PC4 with eigenvalues over 1 explained 12.7 and 10.7%, respectively, of ES variability, with a 72% cumulative percentage of variance.



Graph 5.1: Principal Component Analysis of all ES (both supply and demand). Source: adapted from Lorilla et al. (2020).



Graph 5.2: Scree plot showing the percentage of ES variance which the predictors can explain. Source: adapted from Lorilla et al. (2020).

Table 5.5: Ecosystem service contribution to Principle Component Axes. Source: adapted from Lorilla et al. (2020).

		PC AXIS 1	PC AXIS 2	PC AXIS 3	PC AXIS 4	PC AXIS 5
SUPPLY	FP	**20,461**	6,829	9,557	0,006	0,044
	LP	**24,783**	0,683	0,073	5,523	0,549
	PR	10,243	**15,393**	3,443	0,039	0,405
	CR	0,932	**29,712**	0,175	4,498	0,043
	NS	0,038	0,466	7,346	**51,867**	0,298
	RC	0,010	**30,808**	0,650	0,315	0,667
DEMAND	FP	**22,218**	2,229	9,616	0,219	0,000
	LP	6,201	0,513	2,907	9,987	4,254
	PR	3,886	3,310	7,092	0,008	4,300
	CR	0,053	3,834	**18,809**	15,995	1,122
	NS	**10,788**	0,122	9,800	5,928	5,485
	RC	0,386	6,101	**30,532**	5,615	5,845
CONTRIBUTION		25.0%	23.6%	12.7%	10.7%	7.3%
EIGENVALUE		3.01	2.83	1.53	1.28	0.88

Numbers in bold indicate high contribution to PC axes

5.4 Results on the determinants of the distribution of ES bundles

5.4.1 Bundles of ES supply and demand

Cluster analysis indicated five bundles for ES supply and six bundles for ES demand (Figure 5.4A). For both ES supply and demand, some islands did not present the full set of supply or demand bundles. For example, four out of five supply bundles and four out of six demand bundles were identified for Kefalonia.

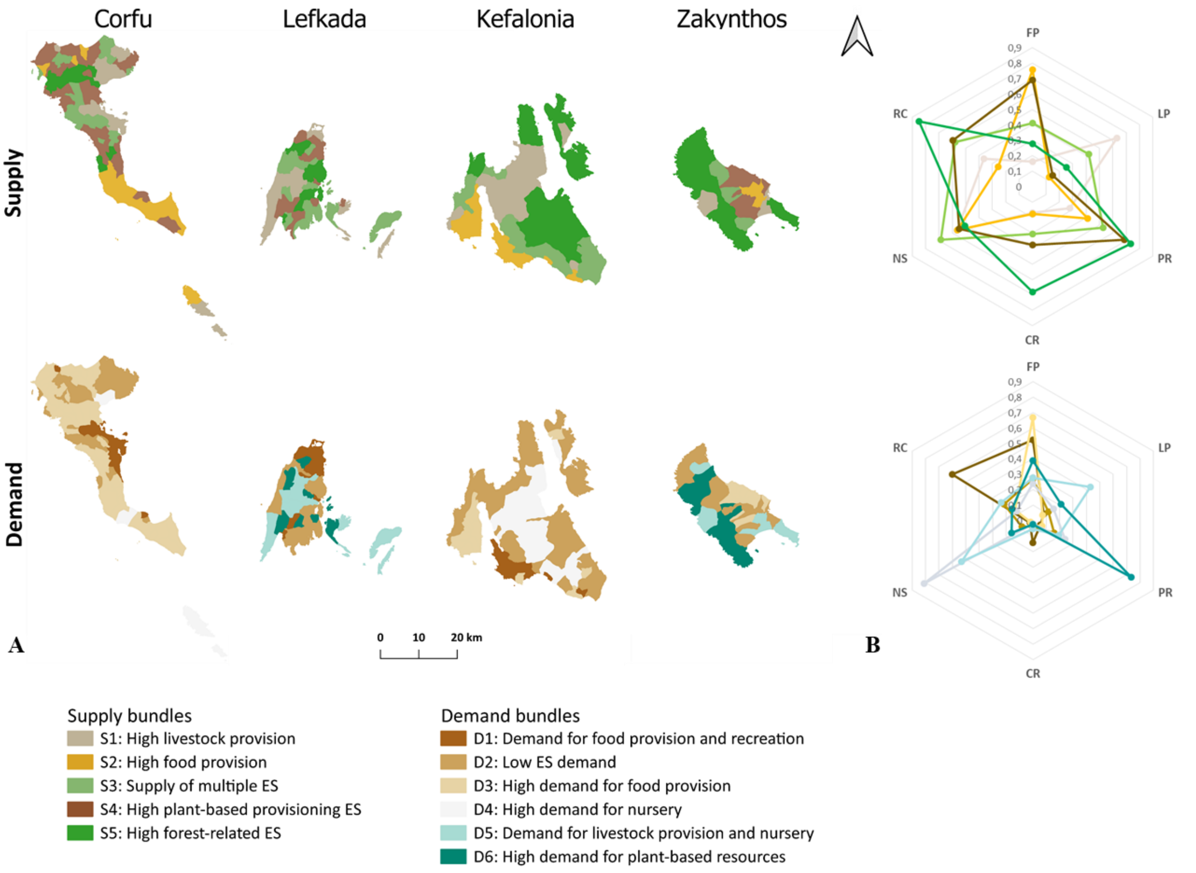


Figure 5.4 Distribution of ES bundles for supply and demand (A), and ES magnitude in each bundle (B). Source: adapted from Lorilla et al. (2020).

Out of the ES supply bundles, S4 (representing olive orchards) contained the highest number of municipal districts (27%), followed by S5 (24%) and S3 (21%), representing highly natural vegetation and mixed ecosystems, respectively. However, S5 covered 31% of the region, followed by S1 (21%), representing sparsely vegetated areas with low ES supply, and S3 (20%) characterized by the provision of multiple ESs (Figure 5.4B and Table 5.6). The cropland related bundle (S2) characterized by high food provisioning service was the smallest in terms of the number of municipal districts and percentage of land area. By contrast, the other agricultural bundle (S4) had high supply values for most ESs (FP, PR, NS, and RC). The positive relationship among PR, CR, and RC that was revealed by the correlations and PCA seemed to form bundle S5, which was mainly located in areas with natural vegetation, high landscape heterogeneity and high ES supply.

Table 5.6: Composition ES bundles in terms of the dominant LULC, main environmental characteristics and dominant co-occurring ESs. Source: adapted from Lorilla et al. (2020).

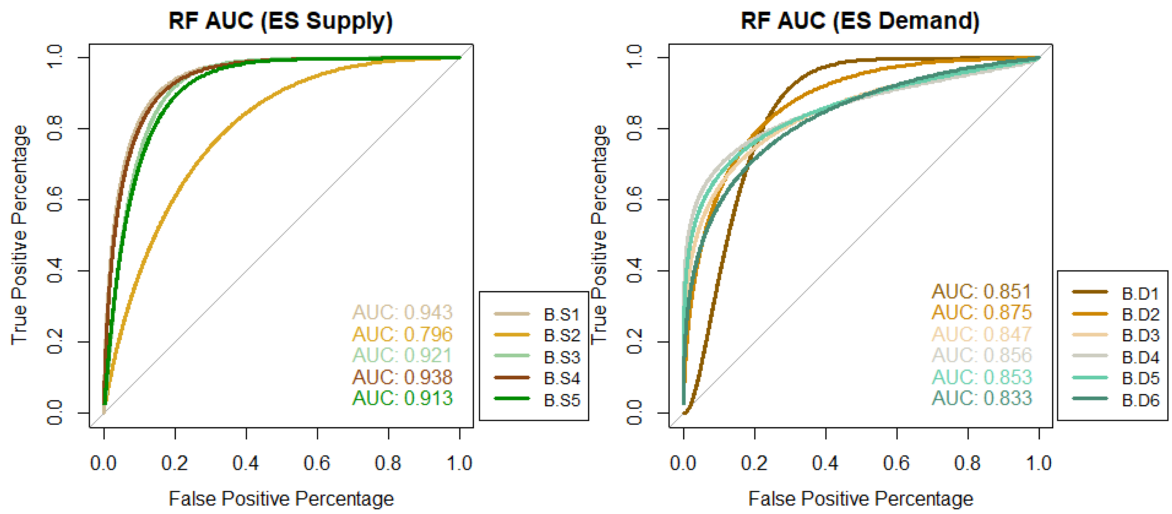
	BUNDLE	DOMINANT LULC AND MAIN CHARACTERISTICS	DOMINANT CO-OCCURRING ES
SUPPLY	**S1**	Sparsely vegetated mountainous and urbanized areas	High livestock provision and moderate nursery maintenance
	S2	Croplands	High food provision and moderate nursery maintenance
	S3	Mixed ecosystems	Moderate provision of multiple ES
	S4	Olive orchards	High supply of plant-based provisioning ES (FP and PR) and moderate recreation and nursery maintenance
	S5	Highly natural ecosystems (mostly forests and shrublands)	High supply of plant-based resources, climate regulation and recreation, and moderate nursery maintenance
DEMAND	**D1**	Urbanized areas	High demand for food provisioning and recreation
	D2	Agricultural areas mixed with patches of natural vegetation	Low demand for ES
	D3	Rural areas	High demand for food provisioning services
	D4	Low vegetation	Maintenance of nursery populations and habitats
	D5	Mountainous and sparsely vegetated areas	Demand for livestock provision and maintenance of nursery populations and habitats
	D6	Mountainous and forested areas	High demand for plant-based resources

The distribution of ES demand separated the study area into two large bundles and four smaller bundles. Bundles D2 (representing agricultural areas mixed with natural vegetation) and D3 (representing rural communities) had the highest extent (87542 and 49101 ha, respectively), as well as the highest number of municipal districts (99 and 88 units, respectively). Both bundles (D2 and D3) had the lowest values of most ES demands out of all bundles (Fig. 4B). Lefkada and Zakynthos represented smaller island complexes, and included the two smallest bundles (D5 and D6). These two 366 bundles each covered 9% of land, and contained six mostly mountainous municipalities with demand for livestock activities (D5) and plant-based resources (D6). The urban bundle of ES demand (D1) was characterized by high human population, low elevation, and flat relief, and had the highest demand for RC, followed by FP. Demand for CR did not characterize any ES demand bundle.

5.4.2 Predictors of ES bundle distribution

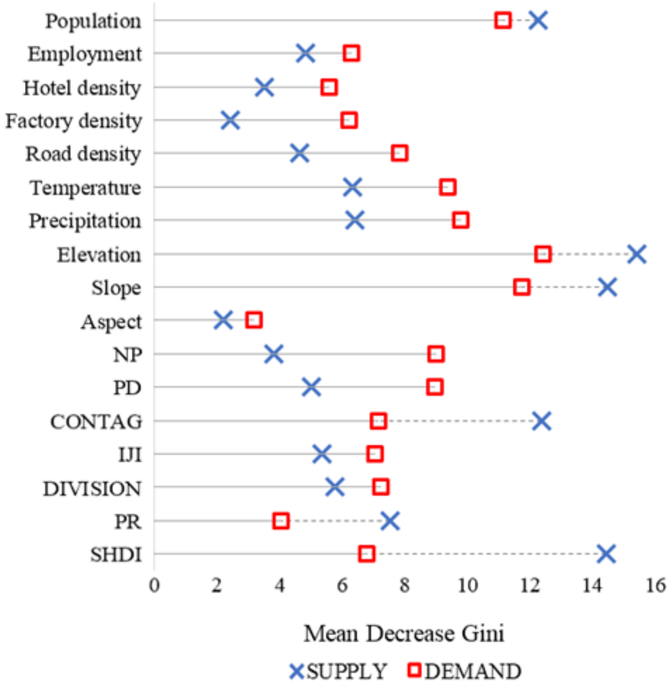
The RF algorithm was applied to predict the distribution of ES supply and demand bundles using 17 socio-economic and ecological variables. During the step by step implementation of the RF model, the most accurate *mtry* and *ntree* values were selected (Tables 5.3). The results of these tests structured the RF model of ES supply with 600 trees, and nine predictors sampled for each tree. For ES demand, the RF model was applied using 1000 trees, and two predictor variables sampled for each tree.

The RF analysis correctly classified 64.1% of ES supply bundles in the training dataset (70% random sample). When considering each ES supply bundle, the accuracy of classification was higher for the three largest bundles (73%, 69%, and 68% for S5, S3, and S4), and lower for S1 (32%), which contained 14% of all municipalities. Despite variability in the accuracy of each supply bundle, the individual AUC–ROC curves revealed a classification capability of 80–94% (Graph 5.3). Furthermore, the multi-class AUC measure showed that the variables used to classify the formed ES supply bundles had 90.9% capability overall. For ES demand, the RF model correctly classified 56% of the original bundles, resulting in a high classification error rate (over 80%) for bundles D1, D4, D5, and D6. However, bundles D2 and D3, which included 60% of the municipal districts on the Ionian Island, were classified correctly with an accuracy of 74.6% and 77.0%, respectively. In addition, multi-class AUC showed that the RF model for ES demand bundles had a classification capability of 79.6%, with individual AUC–ROC curve values ranging between 84.7% and 87.5% (Graph 5.3).



Graph 5.3: Individual AUC– ROC curves of ES supply bundles (left) and ES demand bundles (right). Source: adapted from Lorilla et al. (2020).

The most important variables for the distribution of ES supply bundles were elevation, slope, landscape heterogeneity (SHDI), landscape connectivity (CONTAG), and population (Graph 5.4). In comparison, variables representing elevation, slope, and population were among the most important for ES demand bundles. To evaluate the prediction accuracy of the 17 socio-ecological variables, the RF model was applied to the remaining 30% randomly selected municipal districts (Table 5.7).



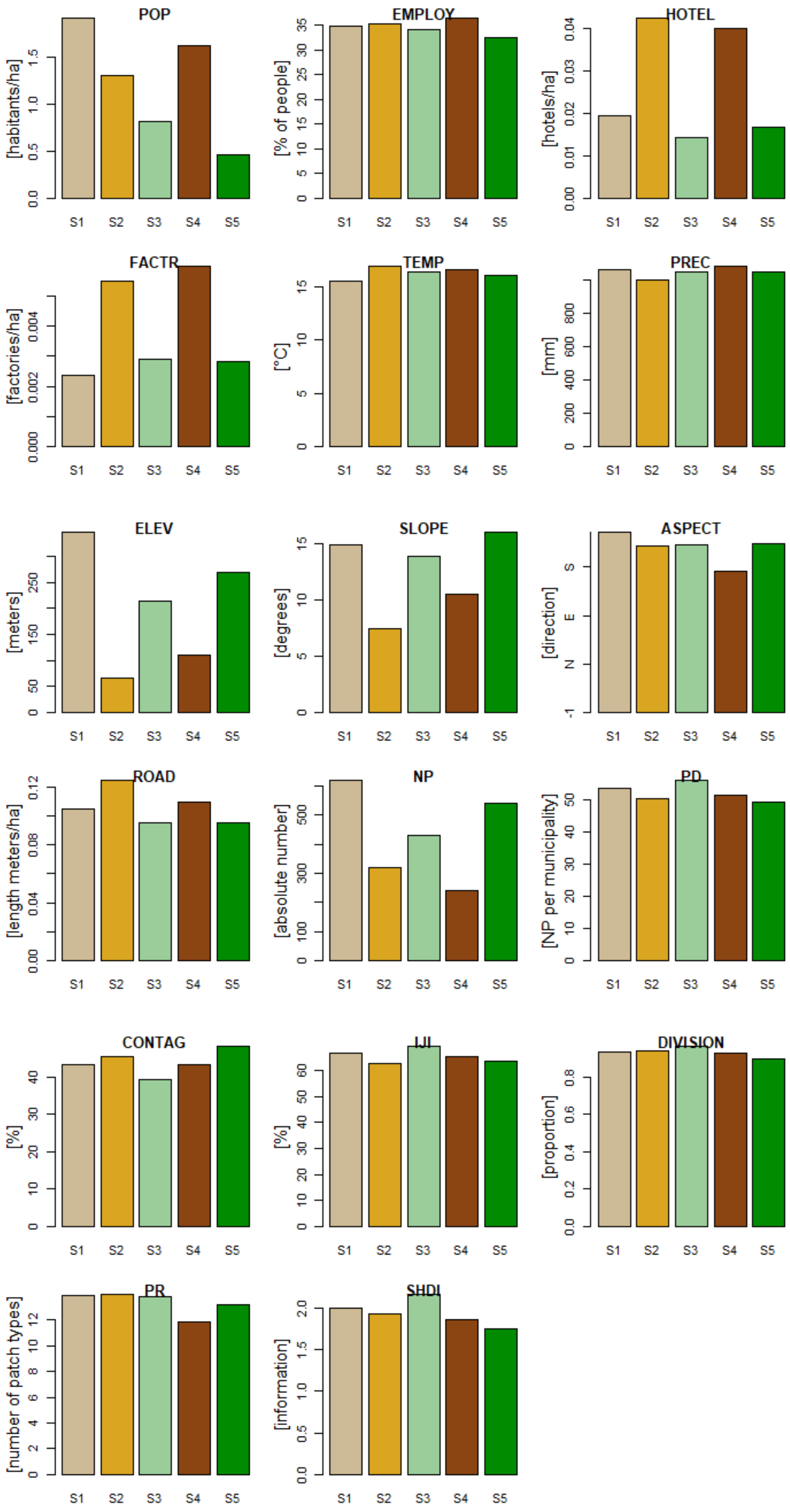
Graph 5.4: Importance of variables for the distribution of ES bundles. Source: adapted from Lorilla et al. (2020).

Table 5.7: Confusion matrix for the prediction rate (%) of RF between original and predicted bundles. Source: adapted from Lorilla et al. (2020).

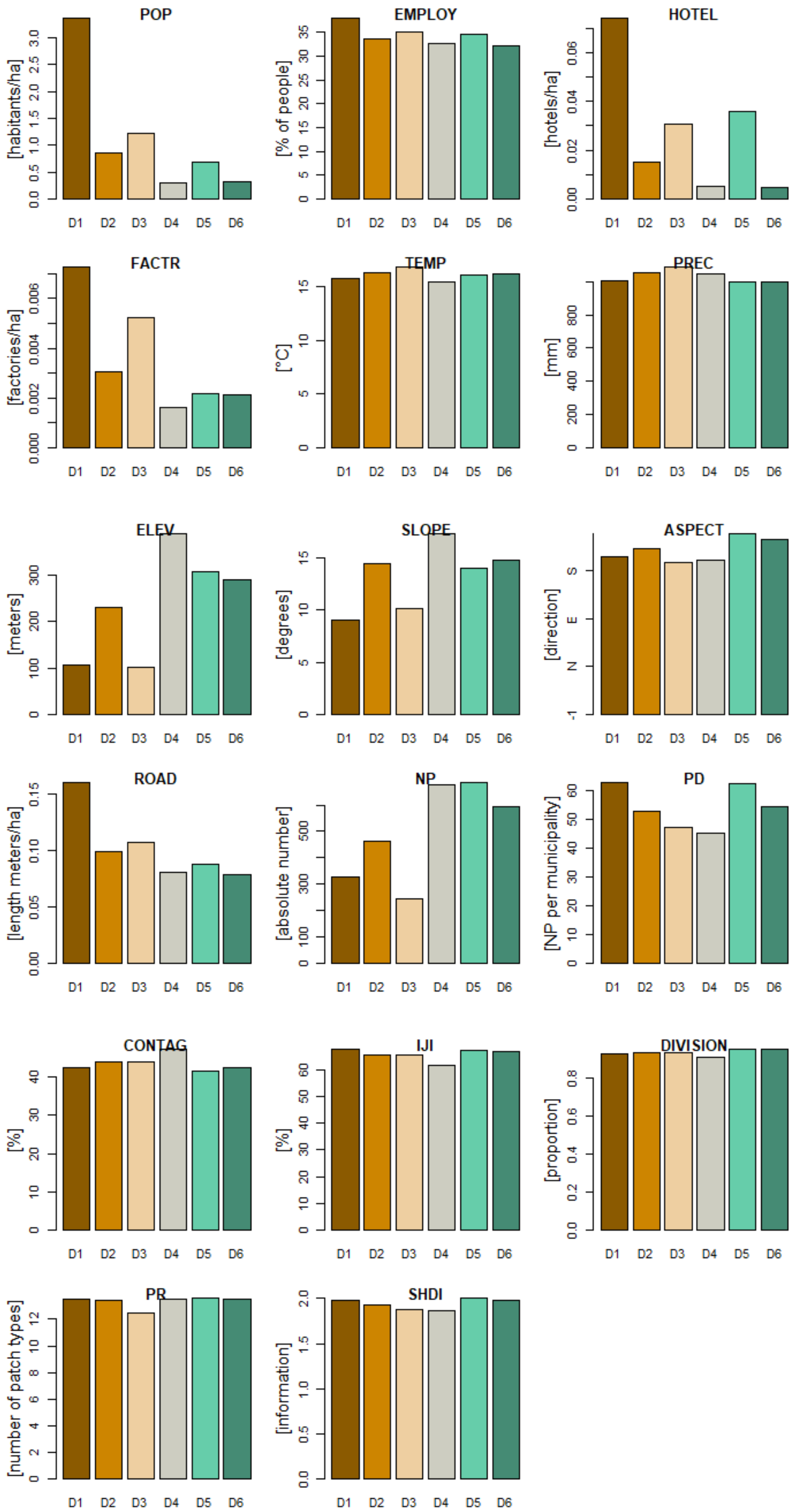
		PREDICTED SUPPLY BUNDLES (%)					**PREDICTED DEMAND BUNDLES (%)**					
		S1	S2	S3	S4	S5	D1	D2	D3	D4	D5	D6
ORIGINAL BUNDLES	S/D 1	35,3	0,0	0,0	0,0	5,0	60,0	3,1	3,7	0,0	0,0	0,0
	S/D 2	0,0	71,4	5,0	0,0	5,0	0,0	75,0	14,8	50,0	88,9	85,7
	S/D 3	35,3	14,3	85,0	10,0	10,0	40,0	18,8	81,5	33,3	0,0	14,3
	S/D 4	17,6	14,3	10,0	80,0	10,0	0,0	0,0	0,0	16,7	0,0	0,0
	S/D 5	11,8	0,0	0,0	10,0	70,0	0,0	3,1	0,0	0,0	0,0	0,0
	D 6	-	-	-	-	-	0,0	0,0	0,0	0,0	11,1	0,0

S/D shows either the original Supply bundles or original Demand bundles. Numbers in bold show correctly predicted municipalities.

The RF model correctly predicted 69.2% of the supply bundles and 58.2% of the demand bundles. The RF supply model performed best with respect to bundles S3 and S4, but performed poorly for bundle S1. Bundle S3 was characterized by low population size, steep slopes, and high landscape diversity (Graph 5.5). By contrast, S4 contained less elevated areas, with higher population size and greater landscape connectivity. High prediction accuracy was also obtained for demand bundles D2 and D3. The most populated demand bundle (see D1 in Graph 5.6) was predicted with an accuracy reaching 60% and 85% based on the RF prediction model and AUC–ROC, respectively. In contrast, bundles D4–D6 had low to zero prediction capability, due to the small number of municipal districts present in these bundles (22 municipalities in total).



Graph 5.5: Mean values of predictor variables for ES supply bundles. Source: adapted from Lorilla et al. (2020).



Graph 5.6: Mean values of predictor variables for ES demand bundles. Source: adapted from Lorilla et al. (2020).

5.5 Discussion

Exploring the associations between ecosystem services and different socio-ecological characteristics offers insights on how important factors contribute to the integrity of the natural environment, which is essential for effective landscape planning (Chen et al., 2020b). With this knowledge, landscape planners and decision-makers can identify ecologically vulnerable areas, and immediately act to mitigate further deterioration.

Stakeholders recognize the landscape as a relevant scale for interacting with different government agencies (Zheng et al., 2019). In addition, administrative boundaries are suitable for identifying socio-ecological systems in a landscape, because management decisions at this level influence the provision and consumption of ESs (Raudsepp-Hearne et al., 2010; Schirpke et al., 2019a). For machine learning in particular, Maldonado et al. (2018) suggested the municipality scale as more appropriate for the selection of socioeconomic indicators in complex socio-ecological systems. However, the effect of scale on the analysis of multiple ESs has been discussed by previous studies (Dou et al., 2018; Grêt-Regamey et al., 2014; Raudsepp-Hearne & Peterson, 2016; Sun et al., 2019; Xu et al., 2017). Nevertheless, a landscape-based ES assessment that focuses on the socio-economic and ecological context constitutes a useful framework for balancing the supply and demand of ESs, and for encouraging sustainability in political decisions.

5.5.1 ES associations

On the supply-side, most studies have demonstrated trade-offs between provisioning and regulating services, while regulating and cultural services mostly exhibit synergistic relationships (Maes et al., 2012b; Raudsepp-Hearne et al., 2010; Turner et al., 2014). Similar results were found in the relationships among ESs on the Ionian Islands, where the supply of food and livestock mostly exhibited trade-offs with the supply of other regulating and cultural services. This pattern indicates the low capacity of field crops, excluding tree crops, and grassland-dominated landscapes to deliver multiple ESs (Lorilla et al., 2018). In comparison, the value of highly natural areas in the provision of regulating and cultural ESs, which has been highlighted in previous studies (Goldenberg et al., 2017), explains the synergistic relationship of RC with CR and PR in Ionian Islands.

On the demand-side, strong correlations were not revealed among ESs. The strongest correlation was obtained for the moderate relationship between the demands for CR and RC, which are connected to the presence of people in urban and rural areas (Baró et al., 2015; Lorilla et al., 2019). Other moderate correlations were obtained in the relationships of NS with FP and LP; thus, in addition to maintaining natural ecosystems (Lopoukhine et al., 2012), protected areas might be characterized by the high demand of livestock animals to carry out grazing activity. If carefully planned, livestock farming under a sustainable regime could meet both biodiversity protection and the strengthening of rural communities (Garnett et al., 2013; Malek et al., 2018).

When connecting the supply and demand of ESs, only FP and LP exhibited synergies between supply and demand, while PR, CR, NS, and RC showed trade-off relationships; thus, spatial similarities appear to exist on one side and spatial mismatches on the other (Lorilla et al., 2019). Schirpke et al. (2019a) obtained similar results, in which the supply of fuel wood, carbon sequestration, and outdoor recreation were negatively correlated with their demand indicators. The supply of LP exhibited strong negative relationship with the demand for FP; thus, grazing activities tend to be mostly situated in regions away from lowland agricultural landscapes, such as mountains (Blondel et al., 2010; Kefalas et al., 2018).

5.5.2 Distribution of ES bundles and predicting factors

Five bundles of ES supply were delineated in the study area, including one low vegetated bundle, two agricultural bundles, one mixed bundle, and one bundle characterized by natural vegetation. In line with previous studies conducted in other areas of the Mediterranean basin (Baró et al., 2017; Quintas-Soriano et al., 2019; Zoderer et al., 2019) and Europe (Mouchet et al., 2017a; Queiroz et al., 2015; Turner et al., 2014), ESs formed similar sets of bundles, in which urban areas, croplands, and forests were clearly distinguished. Thus, the characterization of ES bundles follows a general pattern, regardless of study area (Turner et al., 2014). The results demonstrated that bundles dominated by highly natural areas (S5), followed by agroforest areas (S4), had a high supply of multiple ESs, supporting previous findings (Nieto-Romero et al., 2014). In comparison, all ES demand bundles were characterized by high demand for different ESs, which contrasted the findings of Schirpke et al. (2019a), who documented high demands for multiple ESs in a single bundle.

Different human activities and ecological processes directly or indirectly affect the configuration of landscapes on Mediterranean islands, altering the delivery of ESs (Aretano et al., 2013; Balzan et al., 2018b; Tzanopoulos & Vogiatzakis, 2011). Supporting previous studies, socio-economic and ecological characteristics represent important factors for the formation of ESs, their associations, and/or their bundles (Al-assaf et al., 2016; Dittrich et al., 2017a; Huntsinger & Oviedo, 2014; Kabaya et al., 2019; Lyu et al., 2019a; Mouchet et al., 2014). In particular, the predictor variables selected to explain ES bundles had good accuracy, as indicated by the multi-class AUC values (0.91 for supply and 0.80 for demand). In addition, the individual AUC values for each ES bundle presented good to almost perfect classification accuracy, demonstrating the discriminatory power of the predictors and RF in explaining ES bundles under specific socio-ecological conditions. Previous studies that also used RF to explore the impact of different drivers on ESs obtained high model accuracy (Meacham et al., 2016; Schirpke et al., 2019a); thus, ensemble machine learning techniques are highly reliable for ES assessments.

Based on the RF model, the 17 socio-economic and ecological factors explained the bundles of ES supply, which had high synergistic relationships among the estimated ESs. Supporting previous studies, highly diverse landscapes with mixed ecosystems facilitated synergies among multiple ESs and, hence, the supply of a high number of ESs (Queiroz et al., 2015). An example of this was the mixed ecosystems supply bundle (S3). However, landscape heterogeneity alone does not imply the supply of multiple ESs (Crouzat et al., 2015), because it is the composition of vegetation that determines the capacity of ecosystems to provide services (Yapp et al., 2010). For example, in the highly natural bundle (S5), landscape diversity had the lowest value out of all of the ES supply bundles; thus, homogeneous forests and shrubs positively affect multiple regulating and recreational services (Felipe-Lucia et al., 2018). In addition, agroforest ecosystems provide essential ESs, including food, climate regulation, and recreation, especially when there is a variety of croplands (e.g., olive groves, vineyards, and arable land) (Lorilla et al., 2018; 2019). In contrast, landscape structure did not explain or predict ES demand, as most metrics, except for NP and PD, showed no differences among bundles.

For both supply and demand, population size played a major role in explaining and predicting ES bundles. Specifically, population density in the first demand bundle (D1), which included the three main towns of Corfu, Lefkada, and Kefalonia, was significantly higher than the other bundles. This result reaffirmed that hotspots of ES demand are situated in urban and rural areas (Geijzendorffer et al., 2015). In parallel, cold spots of ES supply exhibited higher population size (Lorilla et al., 2019). Similar results, though not statistically significant, were obtained for the variables of hotels, factories, and road density. Previous studies demonstrated that RF improves accuracy compared to other supervised learning methods (Archer & Kimes, 2008), because it addresses certain issues, such as highly correlated variables, and reduces model overfitting

(Strobl et al., 2008). This might explain the exclusive importance of population density out of all of the socio-economic variables.

Another important variable that strongly contributed to the distribution of ES bundles was topography, including slope and elevation. For instance, the bundles of ESs supply presented a general pattern, in which three bundles (S1, S3, and S5) had higher elevation and steeper slopes, while two bundles (S2 and S4) had a flatter terrain. Topography strongly facilitated the identification of regions where specific landscape processes occur on the Ionian islands and, therefore, where land use change might influence ESs (Kefalas et al., 2019). Interestingly, slope and elevation represented important predictors of ES demand. Thus, topography appears to indicate the location of demands for specific ESs (e.g., mountainous or lowlands). For example, demand for plant-based resources (expressed as the use of biomass for heating purposes) was higher in bundle D6. Thus, people located in mountainous regions might have a greater need for biomass-based heating sources due to the environmental conditions that characterize such areas (Freppaz et al., 2004).

CHAPTER SIX

6 SYNTHESIS

"To avoid problems and conflicts resulting from ES interactions, governments and managers throughout the world are increasingly adopting an ES perspective."

- Tomscha & Gergel (2016), Ecology & Society

Humans fully depend on well-functioning ecosystems, including the services they provide. However, as human population grows, the demand for natural resources are increasing at an alarming rate. This increasing trend, along with economic development and climate change, causes worldwide land transformations and degradation, resulting in depletion of supplies. This suggests that public authorities, including decision- and policy-makers and land managers, have limited knowledge on the importance of natural ecosystems to human well-being. The ecosystem service (ES) framework has become a prerequisite tool for demonstrating the links between nature and society to mitigate further ecosystem deterioration and support landscape management and planning in a sustainable manner. Informing decision-makers and landscape planners are of primary importance, as humans and their management decisions directly affect the status of ecosystems through land use change. The sustainable management of complex ecosystems, such as those of the Mediterranean basin, requires an improved understanding of the spatial and temporal relationships among ESs, as well as the link between ESs and human factors. Especially in the Mediterranean islands, which are widely recognized as biodiversity hotspots, and where human activities have long-affected sensitive ecosystems, identifying possible impacts is crucial. Therefore, this thesis aimed to quantify and map ESs and the relationships among them, and reveal socio-ecological drivers that shape, decrease or enhance the provision of multiple ESs in the Ionian Islands. Five research questions were formulated to address the above issues and guide the analysis: (1) What are the patterns of synergies and trade-offs within ES bundles on Mediterranean island ecosystems? (2) How do ES relationships change across a temporal scale? (3) How well does the supply of ESs and demand by society spatially match? (4) How can land management and planning facilitate maintenance or optimization of the provision of ESs? and (5) Are the composition and the distribution of ES bundles more strongly shaped by social, economic or ecological factors?

6.1 Main findings

The main findings to address the challenges that emerged throughout this dissertation are summarized below. The ultimate goal was to improved our understanding of ES occurrence and the relationship between ES supply and demand to offer important information to decision-makers and landscape planners about the possible impacts that management decisions and actions could cause on the Mediterranean ecosystems of the Ionian Islands.

6.1.1 Assess the spatial and temporal interactions among multiple ESs

Research question 1: What are the patterns of synergies and trade-offs within ES bundles on Mediterranean island ecosystems?

To sustainably manage ecosystems, knowledge about how ESs vary at spatial and temporal scales is required. The findings of Chapter 3 demonstrated that among provisioning ESs, there were mainly synergistic relationships, especially in Zakynthos, where a district separation between the agricultural and natural zone was evident. Also, at both scales of analysis (200 ha hexagonal grid in Chapter 3 and municipal district level in Chapter 5), synergies among the supply of provisioning ESs were found, except for livestock provision, which at the municipality level negatively correlated with other provisioning ESs. In some islands, provisioning ESs followed a different pattern in relation to regulating ESs and recreation, as opposed to other islands, where the supply of provisioning and regulating ESs, and recreation presented spatial congruence. However, areas dominated by mixed olive orchards with natural vegetation delivered the most ESs with high magnitude, showing high synergies within these regions, due to the complex ecological processes that are needed to maintain such ecosystems. This pattern of multi-functional forest and olive orchard ecosystems characterized mostly Corfu and Lefkada, where land abandonment might have affected the synergies between provisioning and other ESs, while agricultural intensification, in Kefalonia and Zakynthos, has created trade-off relationships.

The ES bundle framework facilitated the delineation of coherent groups of ESs with either synergies or trade-offs. The formed ES bundles had distinct compositions and magnitudes, but these were highly dependent on the selected ESs and mapping methods. However, similar results were observed in other study areas, indicating the formation of key ES bundles across different landscapes. Because the tourism and agricultural sector sustains the economy of the Ionian Islands and other Mediterranean areas, the dominant bundles are related to agricultural regions, which, as opposed to the general trend, facilitated synergies among multiple ESs. In parallel, the urban regions inhibit the coexistence of essential ESs. However, Ionian Islands are also characterized by highly natural areas with high provision of regulating ESs and recreation. Especially for recreation, its high supply was present across various ecosystem types of the Ionian Islands, suggesting among others (biodiversity and natural), the high cultural value of the region.

Research question 2: How do ES relationships change across a temporal scale?

Knowledge of the spatial and temporal changes of ES supply and interactions can improve the understanding of underlying processes affecting these changes and optimize the provision of multiple ESs. Chapter 3 also demonstrated that interactions among ecosystem services were not static and changed over time, probably as a result of changing spatial policies directly affecting land cover. As previously discussed, land abandonment has possibly positively affected the supply of multiple ESs. This was also evident in the temporal variations in ES relationships and bundles, where the increase of strength in the synergy between food provision and maintenance of nursery population and habitats suggested the creation of a heterogeneous agricultural landscape. In contrast, forest fires between 2005 and 2015 may have caused a significant decrease in forest ecosystems in Kefalonia and the mountainous areas of Zakynthos. This decreasing trend could also possibly explain the transformation of the trade-off relationships between nursery, represented as habitat diversity, and other ESs related to natural ecosystems. The findings of this thesis on the temporal relationships among ESs, provide useful information to stakeholders and decision-makers, who with their management actions cause land alterations and ecosystem change, and long-term impacts on the provision of multiple ESs.

6.1.2 Identify the spatial congruence between ES supply and demand

Research question 3: How well does the supply of ESs and demand by society spatially match?

The framework followed in Chapter 4 allowed delineating the spatial similarities and mismatches between the supply and demand of three ecosystem services, and identified areas where excess supply and demand exist. The findings showed that the Ionian Islands have a surplus of ES supply in highly natural areas, but that excess societal demand for services is concentrated in urban, rural and agricultural areas. This pattern was mainly due to the absence or long-term presence of people, which either facilitated or inhibited the supply of ESs. In specific, as high societal demand is related to people's presence, cropland areas presented increased supply and demand for food provision and low supply of climate regulation and recreation. However, olive groves, which are located both in lowland and mountainous areas, benefited the supply of all three ESs.

In contrast, spatial mismatches between the supply and demand for climate regulation and recreation were evident, as regions with high demands rarely had high supply. For climate regulation, a possible explanation was the comparatively low regulation capacity in human-dominated land uses, where greenhouse gas emissions exhibit high concentrations. While, the limited access to highly natural areas, as a result of the rough topography or the lack of road networks, inhibit the spatial congruence between the supply of recreation and demand by society. However, the diverse landscapes of the Ionian Islands allowed the existence of a balanced situation in large areas across the region, signifying that human demands for ESs were, for the most part, fulfilled.

Research question 4: How can land management and planning facilitate maintenance or optimization of the provision of ESs?

Information on the matches and mismatches of ES could facilitate efficient spatial planning and the identification of priority areas in need of conservation. Chapter 4 showed that the identification of ES supply and demand hot spots and cold spots could be used to guide the establishment of conservation priorities, in which suggestions on how to maintain or shift the current state in the future are possible to be made. As such, this enables the understanding of how the potential supply of ES correlates with societal demands, leading to important information about where benefits are limited or not to beneficiaries. For example, the mismatch between supply and demand of recreation found in the urban and rural regions of the Ionian Islands could be addressed by an increase of available green spaces, to satisfy the demands for both recreation and climate regulation. Such recommendations would facilitate the adjustment of current management plans and the design of future strategies to ensure the balance between the constant supply of ES and human well-being. More on how the identification of spatial congruencies and mismatches can held guide policy-making is discussed in the next section (Chapter 6.2 Policy implications).

6.1.3 Reveal the socio-ecological determinants of the distribution of ES bundles

Research question 5: Are the composition and the distribution of ES bundles more strongly shaped by social, economic or ecological factors?

Agricultural production, land abandonment, increasing tourism, and forest fires might represent the main factors driving trajectories in ES relationships and among ES bundles. Further research could, therefore, focus on how socio-economic factors influence the provision of ESs and ES bundles, as well as the impacts of possible management policies, driven by human demands, on ESs. Therefore, the analysis conducted in Chapter 5 revealed important factors contributing to the distribution of multiple ESs at the landscape level, in which management decisions are more likely to be taken. In total, 17 variables, representing socio-economic profile, environmental conditions and landscape structure, were tested using a machine learning algorithm (Random Forest) to reveal their contribution to the spatial distribution of ES supply and demand bundles.

Landscape heterogeneity and connectivity represented important predictors of ES bundles located in natural and agricultural areas. In contrast, urban areas, which were strongly linked to ES demand, as chapters 4 and 5 indicated, were explained by population density. In respect to topographic factors, such as slope and elevation, they contributed towards identifying where ES bundles tend to be located. All the mentioned factors presented good to almost perfect ability in predicting and explaining ES supply and demand bundles. Therefore, information on what characterizes specific bundles, along with ES relationships within them, offers an improved understanding of the underlying mechanisms guiding socio-ecological processes, which lead to the supply of ESs. These findings demonstrate that research on ESs should incorporate possible socio-ecological drivers that influence the supply and demand of ESs to improve future management decisions, which may impact the diverse Mediterranean ecosystems of the Ionian Islands. Besides, the diverse landscapes of Ionian Islands play an important role in the balance between the supply and demand of ESs., while the maintenance of such complex landscapes benefit biodiversity conservation, thereby ensuring future provision of ESs.

6.2 Policy implications

Decision-makers and land managers often question how to implement ES assessments into current and future strategies (Bennett & Chaplin-Kramer, 2016; Maes et al., 2018a). In addition, when a decision is taken to allocate resources to produce a single service, a parallel decision is made to prevent the co-existence of multiple services (Burkhard & Maes, 2017).

From a policy perspective, this thesis demonstrates that management actions, which aim to increase specific ESs rather than multiple ESs, should be well planned, designed, and implemented to maintain equilibrium between human well-being and healthy ecosystems. For example, abandoning all agricultural practices, instead of maintaining a well-balanced agricultural and natural landscape, might fail to support nursery populations, in parallel to losing traditional Mediterranean landscapes (Otero et al., 2015; Rühl et al., 2011; Sokos et al., 2013; Van Der Sluis et al., 2014). The case of the Ionian Islands showed that while the forest recreation and high naturalness bundles provide high ES supply, olive groves also seem to supply a variety of provisioning, regulating and cultural ESs over the years. This pattern indicates that a mixed-use agricultural landscape has a higher potential to provide multiple ESs, as opposed to a fully abandoned and homogeneous landscape.

In contrast, agricultural intensification might alter natural characteristics and could create more intense trade-offs with other services, such as water quality, erosion prevention, and recreation opportunity (Bommarco et al., 2013; Power, 2010; Renard et al., 2015; Tscharntke et al., 2005). However, conflicts between provisioning and other ESs found in lowland areas of Zakynthos, suggest that there might be potential for more regulating and cultural services in these areas to avoid a further increase in trade-offs among ESs. By incorporating various crop types mixed with natural zones, instead of specializing on specific types, throughout an agricultural–natural ecosystem can create a more diverse landscape and other services could be enhanced without decreasing other essential ESs (Tolessa et al., 2017).

The increase in tourism requires more space for facilities and activities, with a subsequent loss of natural ecosystems and their services, which is the case for Corfu and Zakynthos (Vogiatzakis et al., 2008). While investing in more accommodation and entertainment facilities seems profitable, it is a temporary decision leading to long-term consequences, as tourism depends on the highly natural and cultural value of the Ionian Islands. If decisions on land modification are not properly managed or not carefully planned, severe impacts both on the environment and tourism might occur in the near future. Therefore, knowledge of the interactions among ESs might prevent future impacts from resource management policies (Lee & Lautenbach, 2016; Willemen et al., 2012), especially when managing heterogeneous landscapes (Spake et al., 2017), such as those in the Ionian Islands.

Despite the negative impact of mass-tourism on natural ecosystems, the preservation of cultural landscapes providing local products and touristic opportunities could contribute to a more sustainable tourism (Kefalas et al., 2018; Vogiatzakis et al., 2008). Regarding recreation, however, which is of high importance in the Ionian Islands, attention is needed due to an increasing focus on nature tourism (also known as eco-tourism). Lacitignola et al. (2007) define eco-tourism as "*responsible travel to areas with relatively high degree of natural values*". However, like any other resource exploitation activity, nature-based tourism requires management and control (Petrosillo et al., 2006). Specifically, recreation and nature tourism consist of activities that have both economic and environmental implications, such as disturbance frequency, development of facilities, unorganized visits, and a lack of knowledge and information (Bell et al., 2007; Petrosillo et al., 2006). Therefore, detailed information is required on the possible impacts of all activities, even those dependent on the quality of the environment more than any other form of tourism. Nonetheless, the synergistic relationship of recreation with other ESs at both scales of analysis (hexagonal grid in Chapters 3 and municipality scale in Chapter 5), revealed the potential of Mediterranean ecosystems to support multiple ESs.

The results of this thesis also demonstrate the importance of acknowledging both supply and demand in ES assessments. This component must be considered in environmental and biodiversity policies that foster the sustainable management of ecosystems. By overlooking these components, the dependency of societal groups on specific ESs, and changes to ES supply triggered by societal demand, cannot be integrated into decision- and policy-making processes (Geijzendorffer et al., 2015). Therefore, ES assessments should consistently suggest realistic alternative policies that ensure the constant future provision of multiple ES.

While food provision showed a satisfying alignment between the supply and demand of ES, the challenge is to maintain their relationship in a balanced state. The different zones of ES flow showed that, in all cases, demand was met, even across the cold spot regions. The realization, however, that a particular agricultural practice is linked to an increase in economic benefits might lead to an increase in social demand. Continuing, high social demand for a specific ES could eventually lead to changes in land use (Wei et al., 2018), which, in most cases, means intensification or abandonment. In addition, agricultural producers tend to either enhance production efficiency through land intensification or shift their activities to other economic sectors leading to land abandonment, with both actions often resulting in the creation of homogeneous landscapes with low potential to support multiple ESs (Burkhard et al., 2016; Lorilla et al., 2018), as previously discussed. The Ionian Islands are characterized by different crop types mixed with significant amounts of natural vegetation, creating the high agricultural value detected throughout the study area (Chapter 3). It is important to maintain this diverse pattern of the agricultural landscape in the Ionian Islands for the continuous supply of multiple ESs, including goods and other regulating and cultural services. The association of species diversity in croplands with the delivery of ESs was also pointed out by previous studies (Bernués et al., 2014; Rositano et al., 2018). Therefore, the sustainability of agricultural ecosystems depends on delivering a complete set of multiple ESs, rather than goods services alone. Agroforestry is one of such land use systems that provides multiple ESs, combining the provision of agricultural and forestry products with non-commodity outputs, such as climate, water and soil regulation, and recreational, aesthetic and cultural heritage values (Fagerholm et al., 2016). This phenomenon explains why different agricultural policies, such as the Common Agricultural Policy (CAP) and the Rural Development Policy, have been reformed to highlight the need to enhance the provision of other ESs, aside from agricultural products (Fernández-Habas et al., 2018). In this way, agricultural activities will not exhibit a trade-off relationship with other regulating and recreational ES, which is a common pattern detected in other areas (Queiroz et al., 2015; Renard et al., 2015; Turner et al., 2014).

To overcome the supply-demand mismatch of carbon sequestration in rural and agricultural areas, policymakers are advised to set a strict CO_2 emissions target to control the demand for climate regulation. This measure is extremely important for tackling climate change (Lutsey & Sperling, 2008). In addition, an increase in the coverage of certain plant species that mitigate the effect of GHG emissions could play a complementary role in climate regulation. However, the impact of urban green spaces on air quality in cities is subject to scientific debate (Baró et al., 2015). For instance, increasing green spaces in urban areas might help regulate the deficit in carbon sequestration, to some extent. Several studies have assessed the role of green space in offsetting urban CO_2 emissions (Escobedo & Nowak, 2009; Yoon et al., 2016). However, it is unlikely that such offsets would meet the requirement for matching the supply and demand of climate regulation, due to gas emissions and air regulation capability being disproportionate

(Chen et al., 2019b). The high congruence of supply and demand signifies the balance between carbon emissions and the capacity of vegetation for climate regulation. This particular zone encompasses a diverse landscape, consisting of similar extents of areas with natural vegetation and areas producing GHG emissions. Maintaining this LULC composition, and regulating future emission policies could potentially facilitate an effective and sustainable management (Sun et al., 2019).

Recreation cold spots located in rural and urban areas presented similar amounts of ES supply and demand, which was attributed to the highly natural and cultural environment that characterizes these islands. In fact, urban systems provide multiple ESs, including provisioning, regulating, and cultural services (Baró et al., 2015). Yet, the slight shortfall of ES supply found in the urban and rural regions of the Ionian Islands could be relieved by an increase in public green spaces, which is considered an effective land management strategy to meet the requirement for satisfying society's demand (Chen et al., 2019b). In connection with climate regulation, the increase of urban green areas could benefit the demand for recreation to some extent, while small amounts of polluted air would still be filtered. For rural regions, maintaining an agricultural landscape with significant amounts of agroforest ecosystems could create highly aesthetic and cultural value (Bernués et al., 2015), facilitating the potential for developing agrotourism activities. Besides, agroforestry is considered a sustainable form of land management that optimizes the use of natural resources (Santiago-Freijanes et al., 2018; Torralba et al., 2016). Regarding natural areas with a high degree of remoteness (excess supply hot spots), the significantly high difference between recreation supply and demand provides opportunities for carrying out outdoor recreation under a sustainable regime. Thus, alternative tourism activities other than concentrated coastal tourism should be promoted in a sustainable way that facilitates local economic development without further degrading important ecosystems, which is a major objective of the ES concept.

6.3 Recommendations for future research

From this work, I contend that future research should focus on the **usability of study results**, such as the ones extracted by this thesis for the **operationalization of the ES concept in practice**. This suggests the comprehensive involvement of stakeholders throughout the research process, as perceived benefits and preferences can strongly differ between stakeholders groups (Rau et al., 2019). Although, in favor of the completion of this research study, eight ESs were quantified, mapped, analyzed and assessed, **the enrichment of the followed framework with more ESs** will provide decision-makers further insights into the importance of ecosystem processes of the Ionian Islands to support essential services. A complete understanding will allow immediate interventions to areas that did not previously exhibit the need for maintenance, to be conserved.

There is a large quantity of literature discussing the factors that influence ESs; however, drivers of ESs and their relationships are often overlooked in the literature. In Chapter 5, I attempted to link various socio-ecological factors to ES bundles and the synergies and trade-offs underpinned beyond a typical correlation. As most landscapes, however, are affected by all categories of driving forces, it may seem appropriate to **limit a study to a subset of driving forces and a specific ecosystem type** to target specific ESs and improve any management strategy that causes a depletion to their supply. Another contemporary issue that is currently gaining attention is the congruence between Biodiversity and ESs. While the value of Biodiversity to the provision of ESs and vice versa is indisputable, **the extent to which the supply of ESs correlate or overlap with Biodiversity** is still a question to be answered. As Biodiversity is often linked to habitat diversity, there are ESs, such as erosion prevention, in terms of compact vegetation density, that may not benefit from such landscape structure. In addition, Biodiversity is either considered a service itself or a condition/state that leads to the provision of ESs.

All in all, the Ionian Islands and, in general, the Mediterranean basin constitute a complex landscape with high biodiversity and cultural value. Therefore, future studies are needed to elucidate the optimal balance between the social and natural environment. The findings of this thesis, in particular, provide useful information on the dynamic nature of ESs in Mediterranean island ecosystems, which offers important information to stakeholders and public agencies, allowing them to develop sustainable landscape management and planning to safeguard ecological integrity and human well-being.

Lastly, I would like to acknowledge the use of the open source software *R Studio Version 1.1.453* (R Core Team, 2019) and the following R packages for employing data analyses and processes (for Chapter 3, 4 and 5), including data preparation, statistical analysis, modeling and data visualization, throughout the implementation of this doctoral thesis. Additionally, the hexagonal grids used in Chapter 3 were generated using patch analyst for ArcGIS (Rempel et al., 2008). Moran's I estimated in Chapter 3 was calculated with Queen Contiguity using the free and open-source software program *GeoDa*. In Chapter 4, the Getis-Ord Gi tool for *ArcGIS version 10.0* was

used to estimate ES hot spots (Mitchel, 2005). Maps for all Chapters were created using the Free and Open Source Geographic Information System *QGIS Madeira version* 3.4.3.

- *caret* version 6.0-84 (Kuhn, 2019)
- *cluster* version 2.1.0 (Rousseeuw et al., 2019)
- *corrplot* version 0.84 (Wei et al., 2017b)
- *factoextra* version 1.0.5 (Kassambara & Mundt, 2017)
- *FactoMineR* version 1.42 (Husson et al., 2019)
- *Hmisc* version 4.2-0 (Harrell & Dunpont, 2019)
- *pROC* version 1.15.3 (Robin et al., 2019).
- *randomForest* version 4.6-14 (Liaw & Wiener, 2018)
- *raster* version 3.0-7 (Hijmans et al., 2019)
- *reshape* (Wickham, 2007)
- *rgdal* version 1.4-6 (Bivand et al., 2019)
- *spatialEco* version 1.2-0 (Evans & Ram, 2019)
- *tidyverse* version 1.2.1 (Wickham, 2017)
- *userfriendlyscience* version 0.7.2 (Peters et al., 2018).

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GLOSSARY

7 ENGLISH TO GREEK GLOSSARY

English term	Greek term (Ελληνικός όρος)
Assessment/-sing	Αξιολόγηση
Biophysical quantification	Ποσοτικοποίηση βιοφυσικών χαρακτηριστικών
Climate regulation	Ρύθμιση του κλίματος
Cultural services	Πολιτισμικές υπηρεσίες
Decision-making	Λήψη αποφάσεων
Determinants/Drivers	Καθοριστικοί/Κινητήριοι παράγοντες
Economic valuation	Οικονομική αποτίμηση
Ecosystems services (ES)	Οικοσυστημικές υπηρεσίες (ΟΥ)
Erosion prevention	Αποτροπή της διάβρωσης
ES associations/relationships	Σχέσεις οικοσυστημικών υπηρεσιών
ES bundles	Δέσμες/Ομάδες οικοσυστημικών υπηρεσιών
ES demand	Ζήτηση για οικοσυστημικές υπηρεσίες
ES distribution	Κατανομή οικοσυστημικών υπηρεσιών
ES supply	Παροχή οικοσυστημικών υπηρεσιών
Excess demand	Πλεονάζουσα ζήτηση
Excess supply	Πλεονάζουσα παροχή
Food provision	Παροχή τροφής
Human well-being	Ανθρώπινη ευημερία
Indicator/Index/Proxy	Δείκτης ή Προσεγγιστικός δείκτης
Livestock provision	Παροχή κτηνοτροφίας
Maintenance of nursery populations & habitats	Διατήρηση σημαντικών πληθυσμών & ενδιαιτημάτων

Maintenance services	Υπηρεσίες διατήρησης
Mapping	Χαρτογράφηση
Materials from timber	Πρώτες ύλες από την ξυλεία
Plant-based resources	Πηγές ενέργειας βάσει φυτών
Predicting factors	Παράγοντες πρόβλεψης
Provisioning services	Προμηθευτικές υπηρεσίες
Recreation	Αναψυχή
Regulating services	Ρυθμιστικές υπηρεσίες
Socio-ecological variables	Κοινωνικό-οικολογικοί παράγοντες
Spatial congruence/matches	Χωρική συμφωνία/αντιστοιχία
Spatial mismatches	Χωρική αναντιστοιχία
Synergies	Συνεργιστικές σχέσεις
Trade-offs	Σχέσεις ανταλλαγής

APPENDIX

8 SUPPLEMENTARY MATERIAL

8.1 Supplementary material of Chapter Three

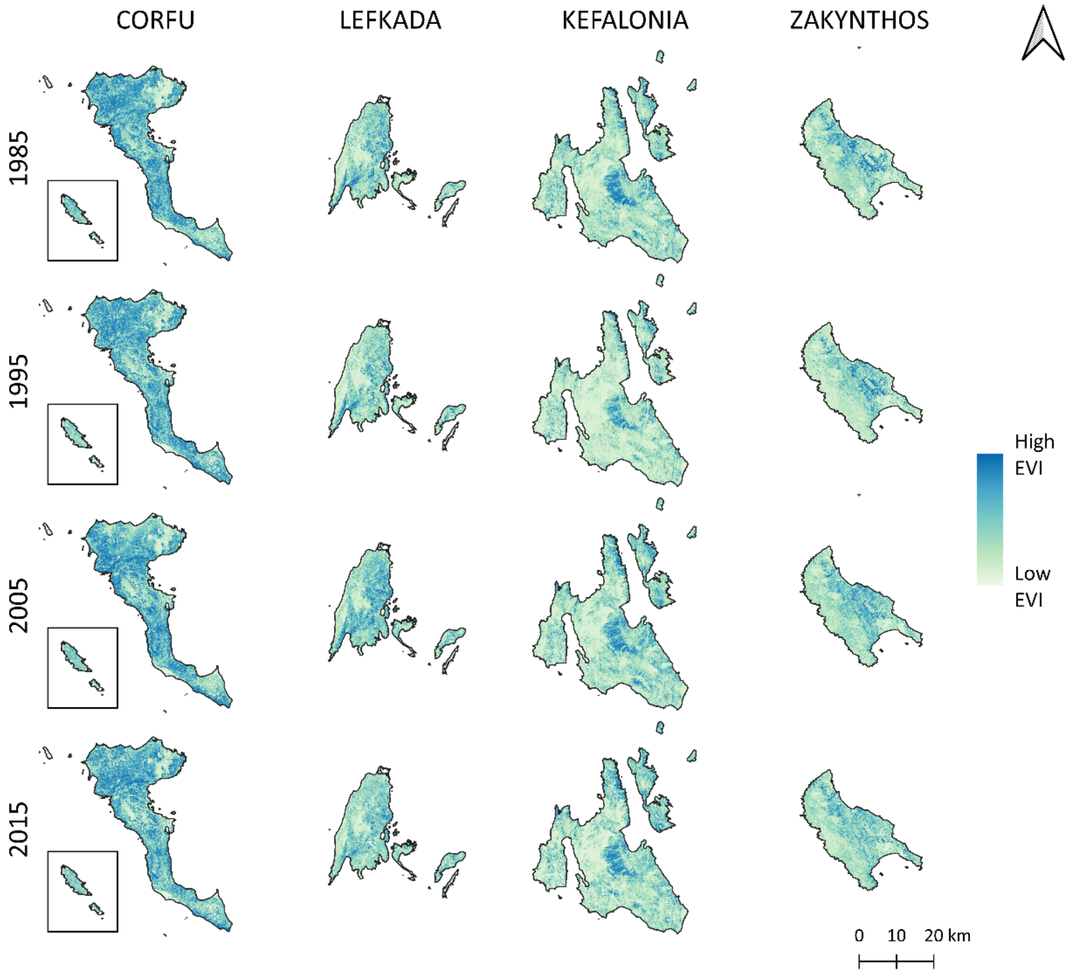

Figure S1: Enhanced Vegetation Index (EVI) for the provision of plant-based resources for the period 1985-2015.

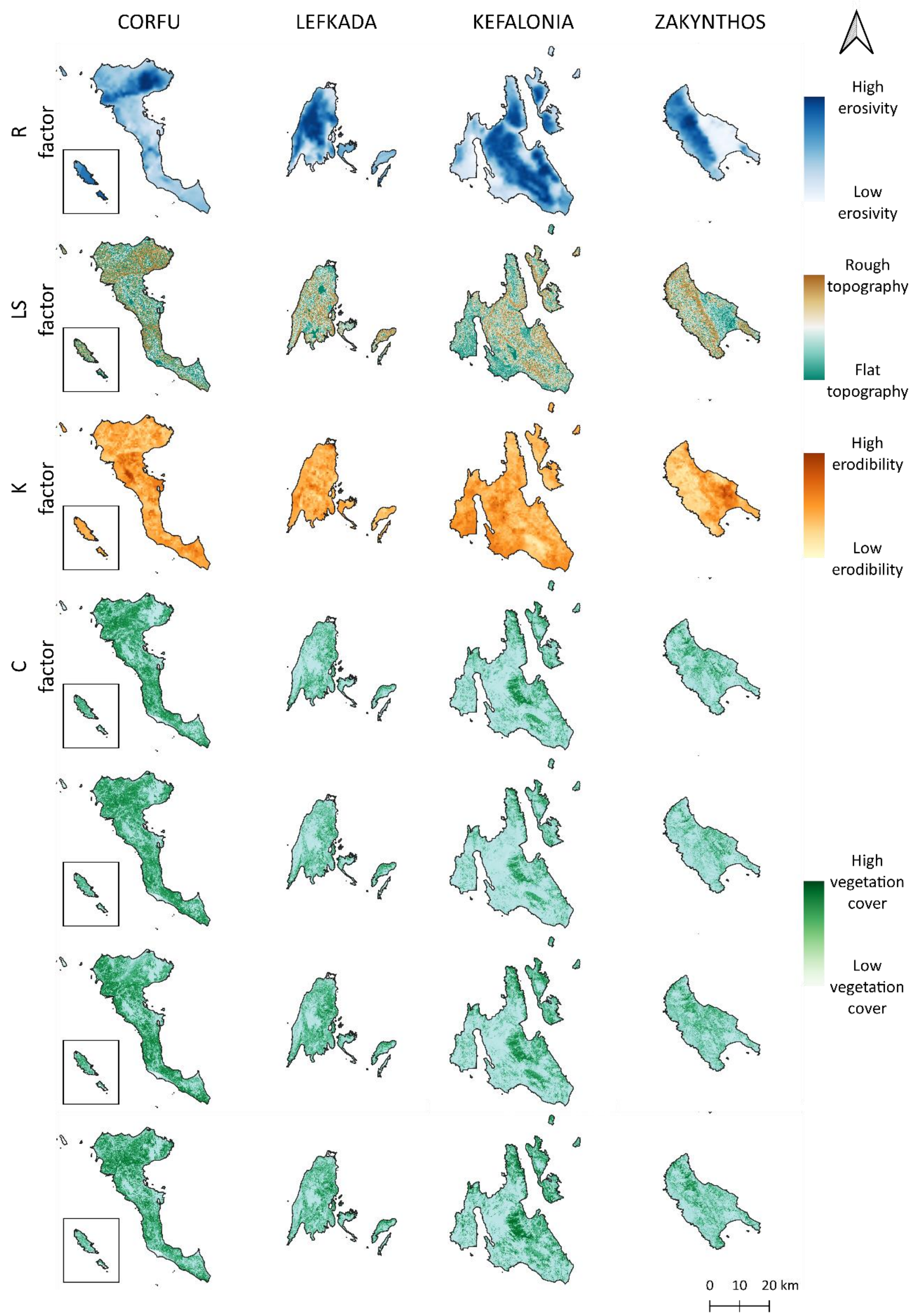

Figure S2: Estimated factors for the actual erosion prevention.

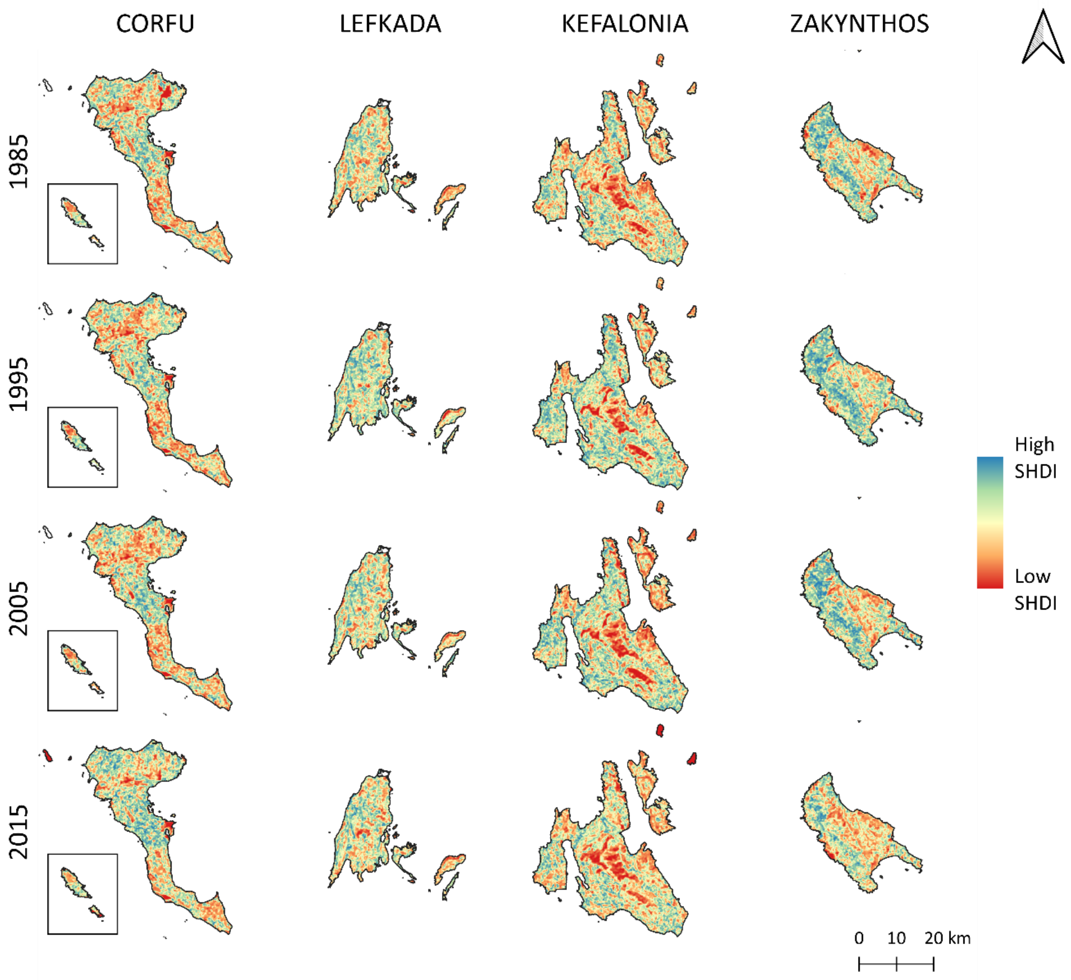

Figure S3: Shannon's diversity index (SHDI) for the nursery service for the period 1985-2015.

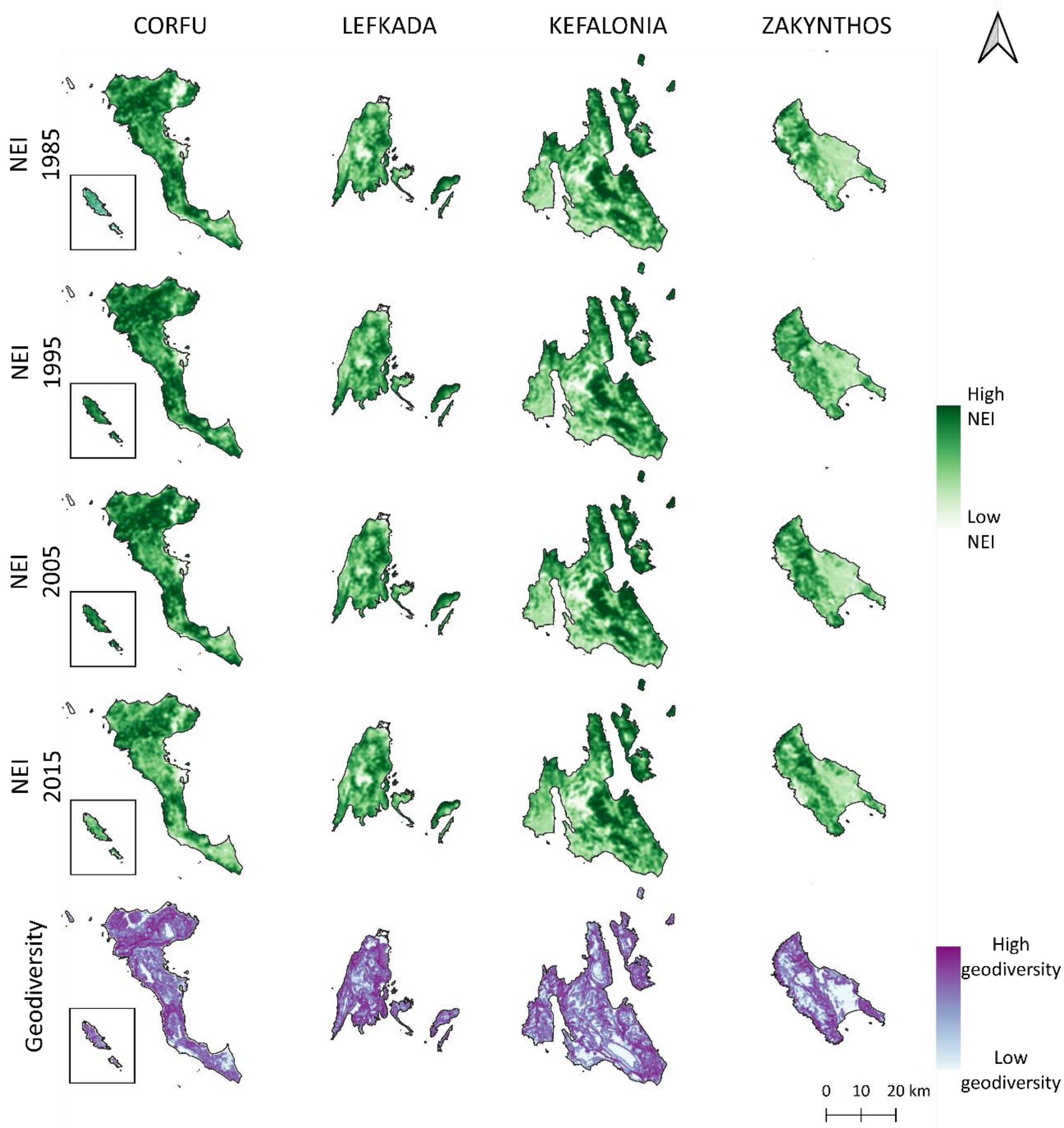

Figure S4: Estimated factors of Naturalness Evaluation Index and Geodiversity for recreation potential.

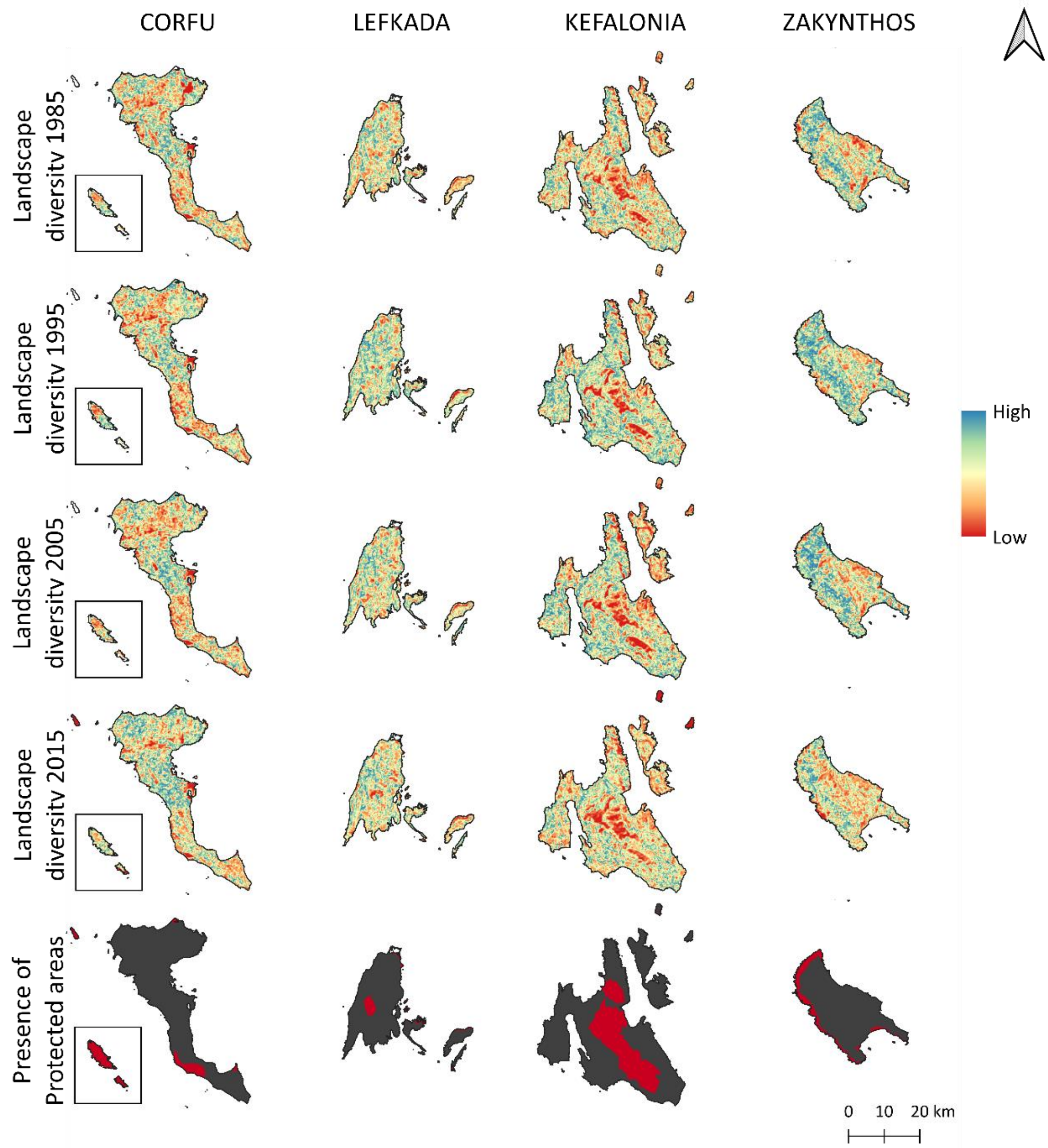

Figure S5: Estimated factors of Landscape diversity and Presence of protected areas for recreation potential.

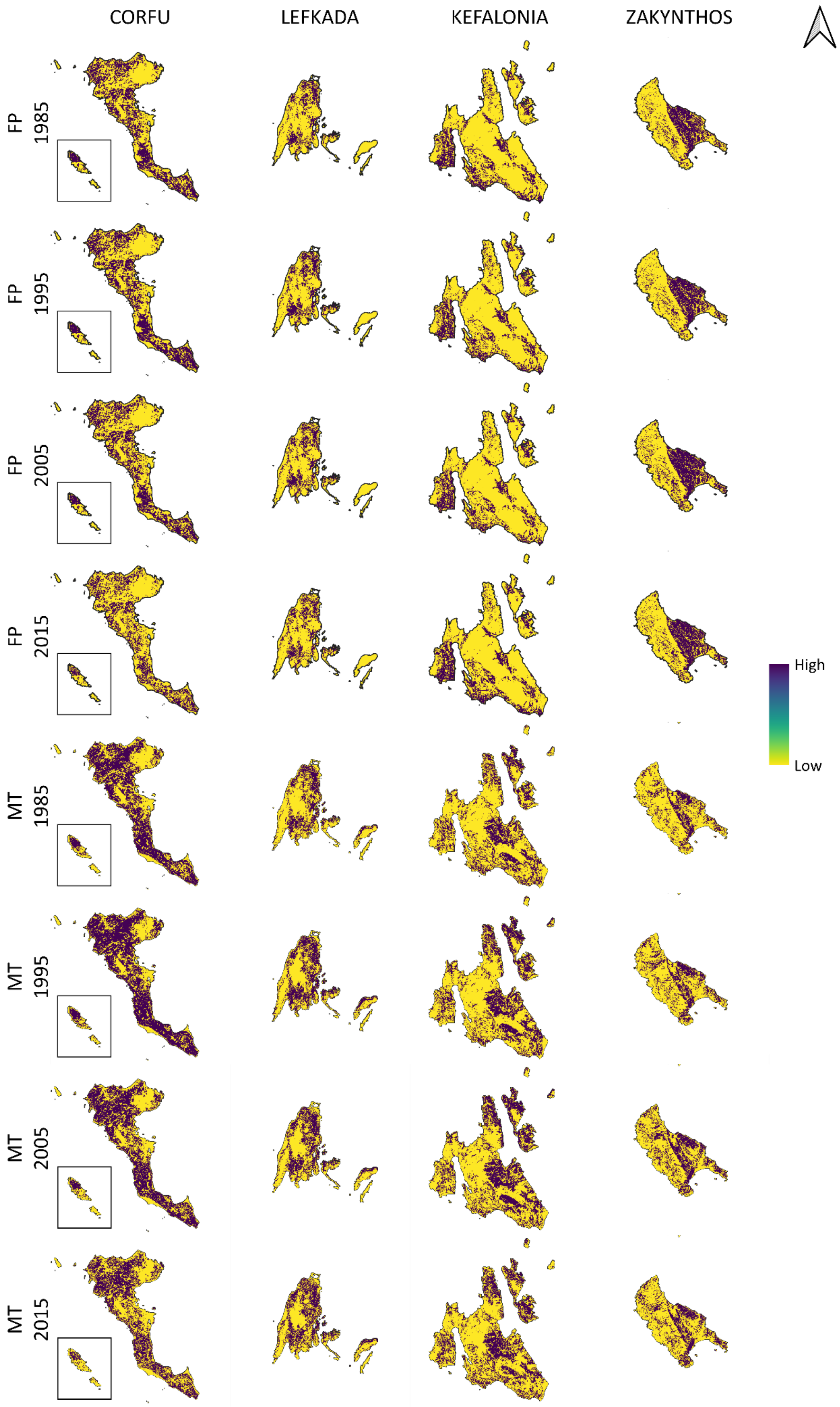

Figure S6: Individual maps of FP and MT supply for the period 1985-2015.

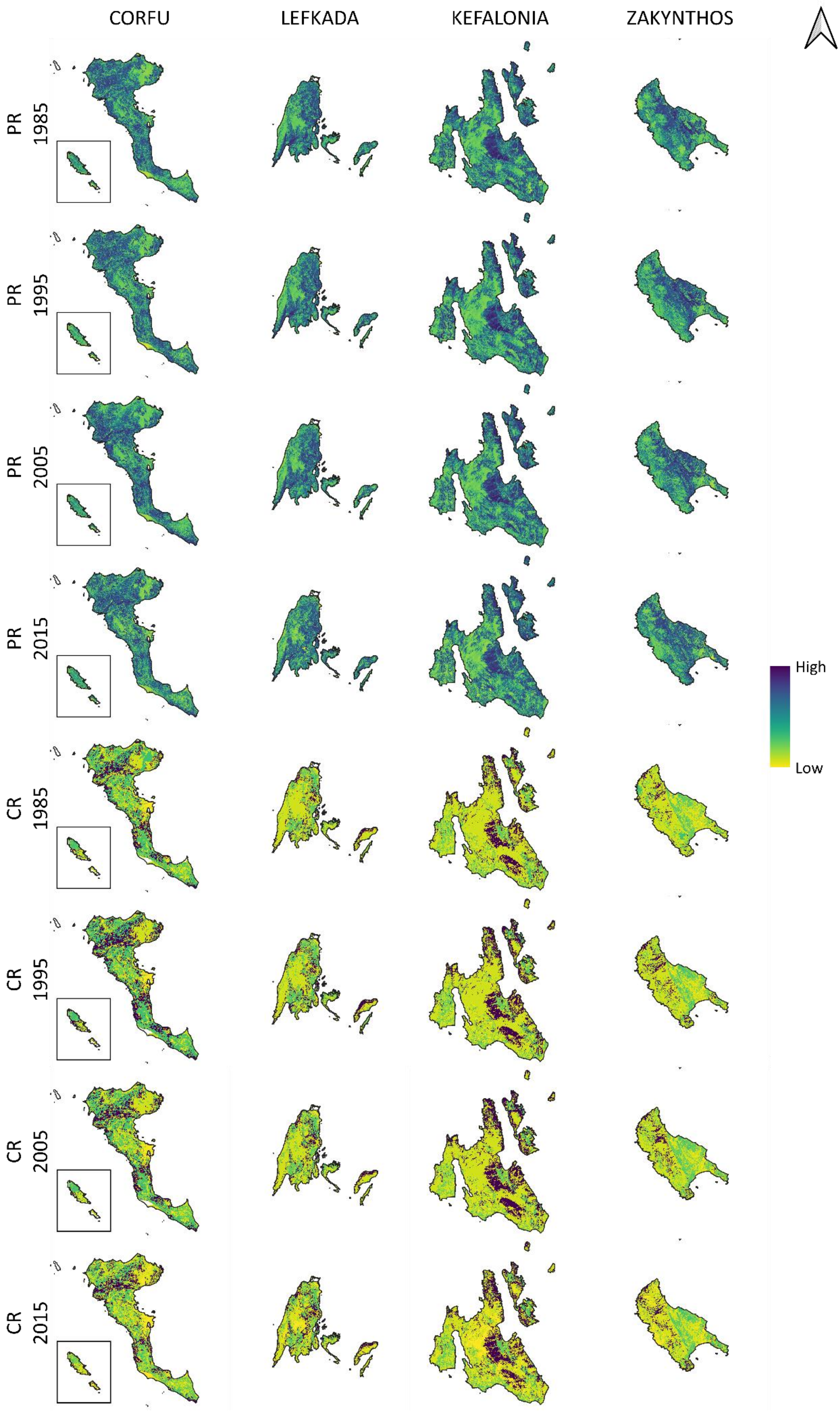

Figure S7: Individual maps of PR and CR supply for the period 1985-2015.

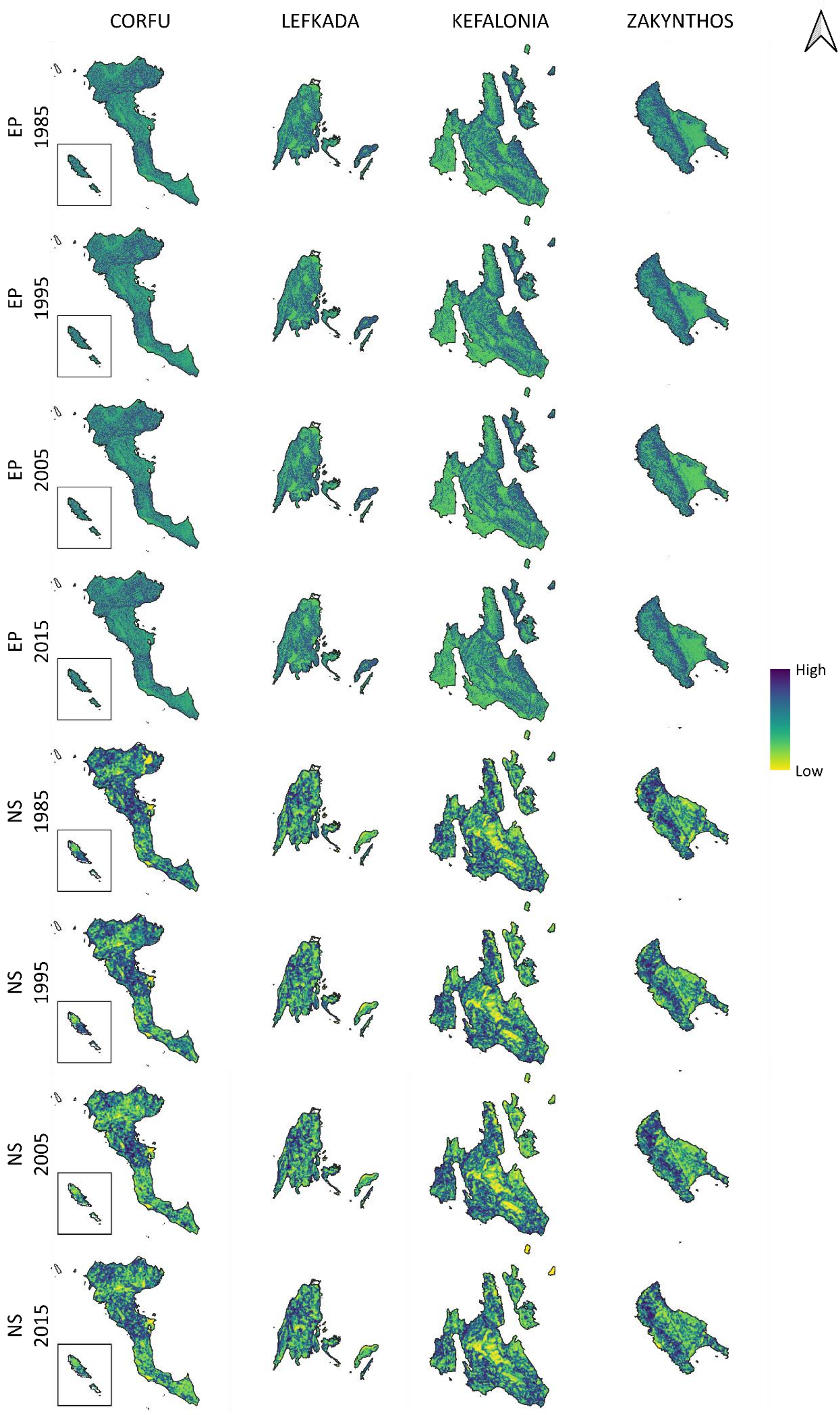

Figure S8: Individual maps of EP and NS supply for the period 1985-2015.

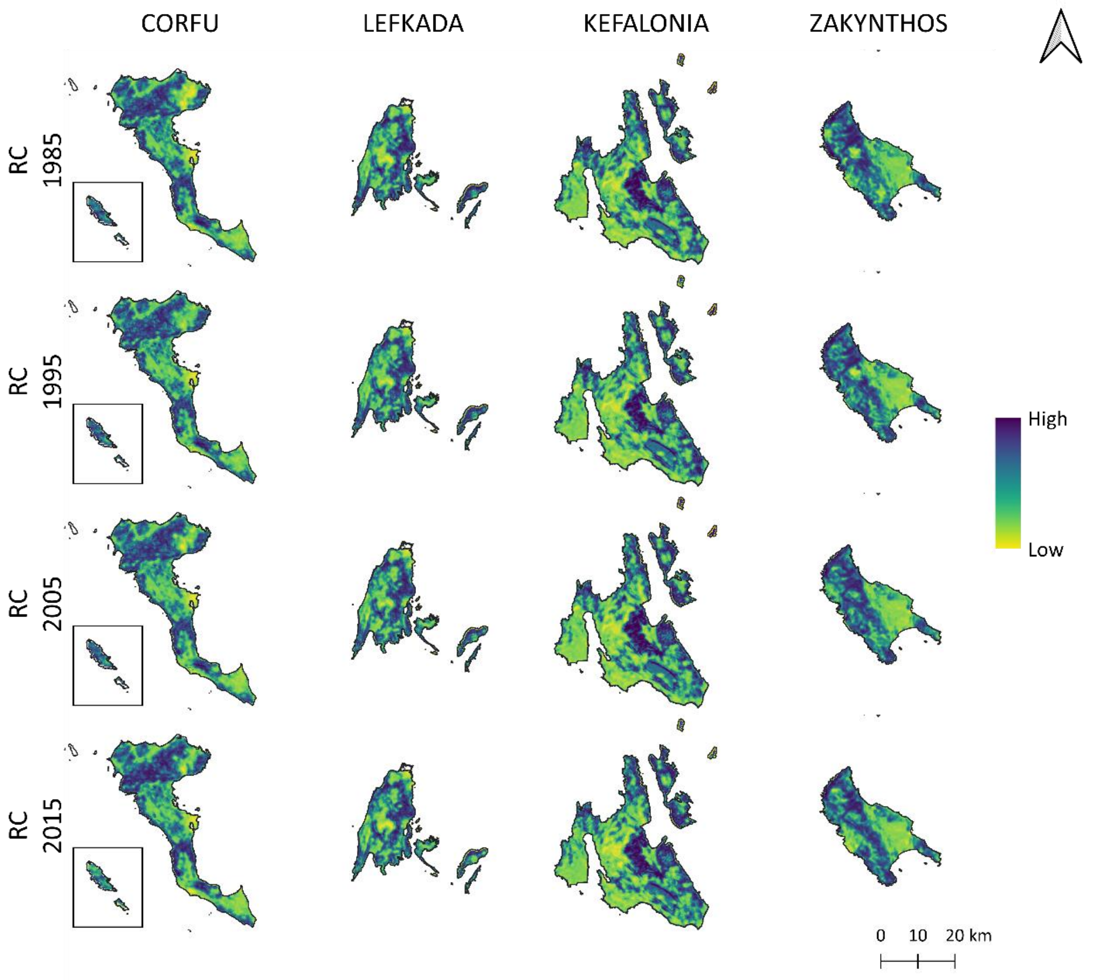

Figure S9: Individual maps of RC supply for the period 1985-2015.

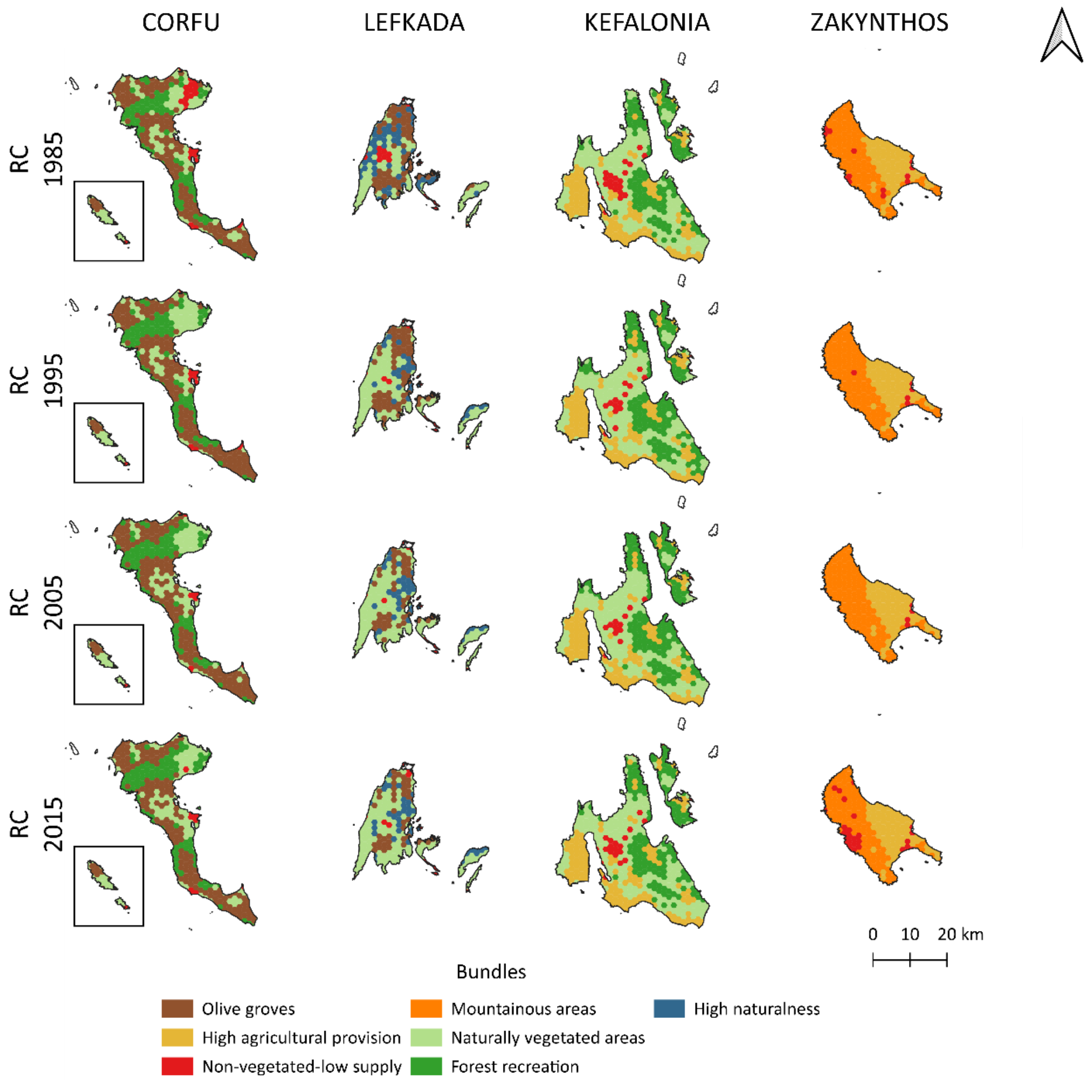

Figure S10: Spatial distribution of ES bundles for the period 1985-2015.

8.2 Supplementary material of Chapter Four

Table S1: LULC class categorization and aggregation.

LULC CATEGORIES	LULC CLASSES	CLASS DESCRIPTION*
HIGH-DENSITY VEGETATION (HD.NV)	Forest	Areas dominated by dense tree vegetation
	Shrublands	Areas dominated by shrubs or maquis species
MEDIUM-DENSITY VEGETATION (MD.NV)	Transitional Vegetation	Areas with floristic elements from both phrygana and shrublands
LOW-DENSITY VEGETATION (LD.NV)	Phrygana	Areas covered by dense phryganic vegetation
	Sparse Phrygana	Areas covered by sparse phryganic vegetation
	Meadow	Areas covered by natural grass
BURNT AND ROCKY AREAS (BUR.ROCK)	Open Areas/Rocks	Open and rocky areas
	Burnt	Land surface areas previously burnt
AGROFORESTRY AREAS (AGR.FOR)	High-Density Olive Orchards	High-density olive trees with natural vegetation patches
CULTIVATION LAND (CULT)	Medium-Density Olive Orchards	Olive orchards
	Vineyards	Vineyards
	Arable land	Arable land used for annual crops (mainly cereals and seasonal vegetables)
	Mixed Cultures	Mosaic of vineyards and arable land where the former prevails
	Other Cultures	Mosaic of vineyards and arable land where the latter prevails
	Permanent Cultures	Tree crops other that olive orchards
SETTLEMENTS (SETTLE)	Urban	Settlements, build-up

* Source: Kefalas et al. (2018)

8.3 Supplementary material of Chapter Five

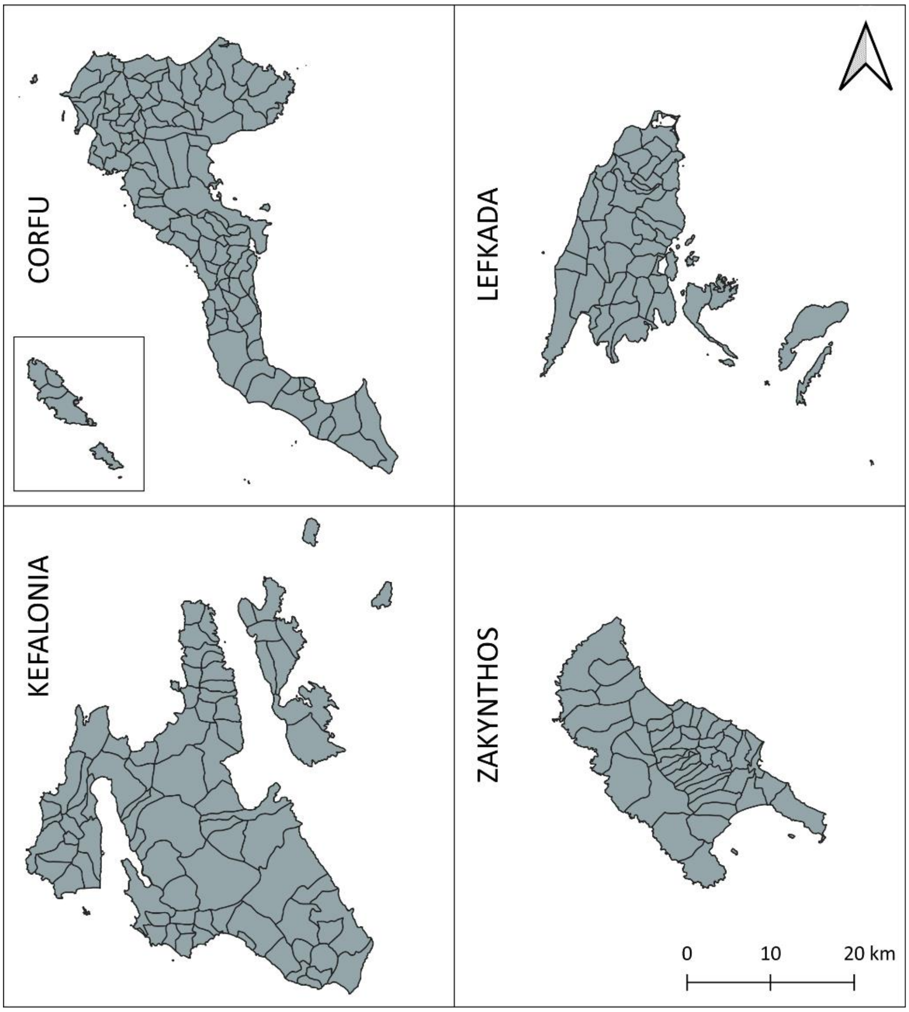

Figure S11: Municipal district division in the Ionian Islands.